Model PRS10
Rubidium Frequency Standard

Operation and Service Manual

Stanford Research Systems

1290-D Reamwood Avenue
Sunnyvale, California 94089
Phone: (408) 744-9040 • Fax: (408) 744-9049
email: info@thinkSRS.com • www.thinkSRS.com

Copyright © 2002 by Stanford Research Systems, Inc.
All Rights Reserved.

Version 1.04 (April 29, 2002)

Introduction **3**

Specifications **4**

Abridged Command List **5**

Theoretical Overview **8**
Rubidium Frequency Standards 8

PRS10 Overview **11**
Block Diagram 11
Ovenized Oscillator 11
Frequency Synthesizer 11
Physics Package 13
Control Algorithm 13
Initial Locking 14
Locking to External 1pps 14
CPU Tasks 18

Applications **19**
Interface Connector 19
Configuration Notes 19
Hardware Notes 20
Operating Temperature 21
Frequency Adjustment 21

RS-232 Instruction Set **22**
Syntax 22
Initialization 22
Frequency Lock-loop Parameters 24
Frequency Synthesizer Control 28
Magnetic field Control 29
Frequency Control 31
One pulse per second control 31
1PPS Locking Control 33
Analog Control 35
Analog Test Voltages 36
Status Bytes 37

Calibration Procedures **40**

Circuit Description **41**
Schematic RB_F1 (sheet 1 of 7) 41
Input Power 41
Voltage Reference 41
Crystal Oscillator 41
Crystal Heater 43
Schematic RB_F2 (Sheet 2 of 7) 43
Temperature Control Servos 43
Conversion to 10MHz TTL 44
Photocell Amplifier 45
Signal Filters for Oscillator Control 45
Analog Multiplexers 46
Schematic RB_F3 (Sheet 3 of 7) 46
Microcontroller 47
RS-232 49
12 Bit A/D Conversion 49
12-Bit Digital to Analog Converters 49
Magnetic Field Control 49
Phase Modulation 50
1PPS Output 50
1PPS Input Time-Tag 50
Schematic RB_F4. (Sheet 4 of 7) 51
High Resolution, Low Phase Noise, RF Synthesizer 51
RF Output Amplifier 52
Step Recovery Diode Matching 52
Analog Control 53
Schematic RB_F5 (Sheet 5 of 7) 53
Power Supply, Lamp Control and 1PPS Timing PCB 53
Linear Power Supplies 53
Lamp Regulator 54
1PPS Input Time-Tag 54
1PPS Output Pulse Delay 55
Baseplate Temperature Sensor 56
Schematic RB_F6 (Sheet 6 of 7) 56
Resonance Cell and Lamp Heaters 56
Resonance Cell 56
Discharge Lamp 56
Schematic RB_F7 (Sheet 7 of 7) 57
Connector Interface Board 57

Appendix A: Frequency Synthesizer Table **59**

Appendix B: Precision Frequency Measurement **61**
Set-up for an SR620 62
Four input connections: 62

Four input setups: 62
"Coarse" Frequency Measurements 62
"Fine" Frequency Measurements 62

Parts List for Revision H 64

PRS10 Rubidium Frequency Standard Introduction

The PRS10 is a ultra-low noise 10 MHz frequency standard which disciplines an SC-cut ovenized oscillator to a hyperfine transition in the ground state of rubidium.

The PRS10 was designed to fill a variety of communication, synchronization, and instrumentation requirements. The phase noise of the 10 MHz output is low enough to be used as the reference source for cellular synthesizers. The unit's short-term stability and low environmental coefficients make it an ideal component in network synchronization systems. Also, the low aging rate makes it an excellent choice as a timebase for precision frequency measurements.

The unit is compatible in fit, form, and function to the Efratom FRS frequency standards, with improvements in features and performance. The PRS10 allows closed case diagnostics and calibration via an RS-232 interface, its digital synchronous detection and filtering eliminate spurs on the 10 MHz output, and the PRS10 has 1000x less phase noise than the Efratom unit (-130 dBc vs. –90 dBc at 10 Hz).

The PRS10 can time-tag an external 1pps input with very high resolution. These values may be reported back via RS-232 and/or used to phase lock the unit to an external reference (such as GPS) with a time-constant of several hours. This feature can provide Stratum 1 performance at a very low cost.

In addition to reading time-tag results, the RS-232 interface allows the user to set the frequency, adjust the phase of the 1pps output, read the value of virtually every parameter (lamp drive level, rf level, temperature set point of the crystal, lamp, and resonance cell, and 10 MHz output level) and measure many "test-points" (lamp light level, heater currents, power supply voltages, and case temperature.)

The PRS10 establishes a new level of features and performance in atomic frequency standards. Its design provides for the lowest phase noise and easiest path to system integration of any rubidium frequency standard available.

		Units
Output		
Frequency	10 (Sine wave into 50Ω)	MHz
Amplitude	0.5 ± 10% (about 1.41V_{pp} or +7 dBm)	V_{rms}
Accuracy	±5x10^{-11} (at shipment)	Δf/f
Allan variance	< 2x10^{-11}(1s), < 1x10^{-11}(10s), < 2x10^{-12}(100s)	Δf/f
SSB phase noise	<-130 (10Hz), <-140 (100Hz), <-150 (1kHz)	dBc/Hz
Spurious	<-130 (100kHz B.W.)	dBc
Harmonics	<-25	dBc
Return loss	> 25 (at 10MHz)	dB
Temperature	±1x10^{-10} over -20°C to +65°C baseplate	Δf/f
Voltage	< 2x10^{-11} for a 1V_{dc} supply change	Δf/f
Magnetic field	< 2x10^{-10} for 1 Gauss field reversal	Δf/f
Retrace	±5x10^{-11} (72 hr off then 72 hr on)	Δf/f
Settability	< 5x10^{-12}	Δf/f
Trim Range	±2x10^{-9}	Δf/f
Time to lock	< 6 (starting at 25°C)	minutes
Time to 1x10^{-9}	< 7 (starting at 25°C)	minutes
Other Electrical		
Power supply	+24.0 (nom), +22 (min), +30 (max)	Vdc
Supply current	2.2 (warmup) , 0.6 (steady-state at 25°C)	A
Protection	± 30 (to any pin except rf output)	V_{dc}
RF protection	100 (stable with any termination)	mA
Ext calibration	0-5.00	V_{dc}
Cal reference out	5.00 ± 0.05	V_{dc}
RS-232	9600 (8 bits, no parity, 1 stop bit, 0V/5V levels with x on/x off protocol)	baud
1pps measurement	±10 (accuracy), 1 (resolution)	ns
1pps output set	±10 (accuracy), 1 (resolution)	ns
Miscellaneous		
Temperature	-20 to +65 (baseplate)	°C
Storage	-55 to +85	°C
Size	2.00 x 3.00 x 4.00	inches
Weight	1.32	lbs
Warranty	2	years
Baseplate threads	4-40 (4 places)	
Connector	Mates with ITT/Cannon DAM11W1S series	

Abridged Command List

Commands consist of two-letter ASCII mnemonics. A command may be followed one or more numeric values, and punctuation. Command sequences end with a carriage return (ASCII 13_{10}). All commands are case insensitive. Spaces (ASCII 32_{10}) and linefeeds (ASCII 10_{10}) are ignored.

A command followed by a value is used to set a parameter to the value. A command followed by an exclamation point (! or ASCII 33_{10}) indicates that the current value should be saved to EEPROM to be used as the initial value after the next reset. A command followed by a question mark (? or ASCII 63_{10}) is used to request that the current value be returned. A command followed by an exclamation point and a question mark is used to return the EEPROM value.

For example, the gain parameter determines the time constant used to lock the 10MHz oscillator to the rubidium hyperfine transition. Examples of the four forms of the gain parameter command are:

```
GA?     ;returns the current value of the frequency lock loop gain parameter.
GA7     ;sets the frequency lock loop gain parameter to 7.
GA!     ;writes the value of the gain parameter to EEPROM for use after reset.
GA!?    ;returns the value of the gain parameter which is stored in EEPROM.
```

All strings returned by the unit are terminated with a carriage return (ASCII 13_{10}). In the verbose mode, strings are preceded with a linefeed (ASCII 10_{10}) and terminated with a carriage return and a linefeed. If more than one value is returned by a command the values will be separated by a comma (ASCII 44_{10}).

When a unit is first turned “on”, it will send the string “PRS_10” (without the quotes) followed by a carriage return.

Only commands in **bold type** are available to the end-user. The other commands are “factory only” commands which disabled at the factory.

Query Value	Set Value or Activate	Write EEPROM	Query EEPROM	Description
Initialize				
RS?	**RS 1**			Restart
VB?	**VB *value***			Verbose mode
ID?				Read ID string
SN?	SN *value*	SN!	**SN!?**	Read unit serial number
ST?				Read six status values
LM?	**LM *value***	**LM!**	**LM!?**	Lock pin mode
	RC 1	RC!		Recall factory calibration
Freq. Lock				
LO?	**LO *value***			Frequency lock loop status
FC?	**FC *high,low***	**FC!**	**FC!?**	Frequency control values
DS?				Read detected signals (ω and 2ω)
SF?	**SF *value***			Set frequency offset
SS?	SS *value*	SS!	**SS!?**	Set Slope (SF calibration)
GA?	**GA *value***	**GA!**	**GA!?**	FLL Gain parameter
PH?	PH *value*	PH!	**PH!?**	Phase angle parameter
SP?	**SP *r,n,a***	**SP!**	**SP!?**	Set synthesizer parameters
Magnetic Tuning				
MS?	**MS *value***			Magnetic switching
MO?	**MO *value***	**MO!**	**MO!?**	Magnetic Offset
MR?				Magnet read
1PPS Lock				
TT?				Time-tag (1pps input)
TS?	TS *value*	TS!	**TS!?**	Time slope cal. (1pps input)
TO?	**TO *value***	**TO!**	**TO!?**	Time-tag offset
	PP *value*			Place pulse (1pps output)
PS?	PS *value*	PS!	**PS!?**	Pulse slope cal. (1pps output)
PL?	**PL *value***	**PL!**	**PL!?**	Phase lock (to 1pps input)
PT?	**PT *value***	**PT!**	**PT!?**	Phase lock time constant
PF?	**PF *value***	**PF!**	**PF!?**	Phase lock stability factor
PI?	**PI *value***			Phase lock integral term

Query Value	Set Value	Write EEPROM	Query EEPROM	Description
D/A Control				
SD0?	SD0,*value*	SD0!	**SD0!?**	Set DAC (RF amplitude)
SD1?	SD1,*value*	SD1!	**SD1!?**	Set DAC (1pps delay)
SD2?	SD2,*value*	SD2!	**SD2!?**	Set DAC (lamp intensity)
SD3?	SD3,*value*	SD3!	**SD3!?**	Set DAC (lamp temperature)
SD4?	SD4,*value*	SD4!	**SD4!?**	Set DAC (crystal temperature)
SD5?	SD5,*value*	SD5!	**SD5!?**	Set DAC (cell temperature)
SD6?	SD6,*value*	SD6!	**SD6!?**	Set DAC (10 MHz amplitude)
SD7?	SD7,*value*	SD7!	**SD7!?**	Set DAC (RF deviation)
Analog Test	(12-bit values)			
AD0?				Spare (J204)
AD1?				+24V(heater supply) / 10.
AD2?				+24V(electronics supply) /10
AD3?				Drain voltage to lamp FET / 10
AD4?				Gate voltage to lamp FET / 10
AD5?				Crystal heater control voltage
AD6?				Resonance cell heater control
AD7?				Discharge lamp heater control
AD8?				Amplified ac photosignal
AD9?				Photocell's I/V converter / 4
AD10?				Case temperature (10 mV/°C)
AD11?				Crystal thermistors
AD12?				Cell thermistors
AD13?				Lamp thermistors
AD14?				Frequency calibration pot
AD15?				Analog ground
Analog Test	(8bit values)			
AD16?				VCXO varactor voltage
AD17?				VCO varactor voltage
AD18?				AGC for RF
AD19?				RF PLL lock signal

Theoretical Overview of Rubidium Frequency Standards

Rubidium is an alkali metal (like lithium, sodium, potassium and cesium). There are two naturally occurring isotopes of rubidium, Rb85 and Rb87, which have relative abundances of 72% and 28% respectively. The metal has a melting point of 39°C.

The alkali metals behave similarly: they have one electron outside an inert core. Most of the chemical, electronic and spectroscopic properties of these elements are determined by this outer electron. The deep red glow of a low power rubidium discharge lamp is due to the resonance line transitions of the outer electron as it emits a red photon and drops back to the ground state.

The ground state of Rb87 is split by a very small energy due to the relative orientation of the magnetic spins of the electron and the nucleus. The split corresponds to the energy of a photon with a (microwave) frequency of 6.834,682,612,8 GHz. It is this hyperfine transition frequency which will be used to stabilize the 10 MHz output of the PRS10.

To see how this is might be done, Figure 1 shows a typical physics package which uses a discharge lamp, an isotopic filter, and a resonance cell. We will see that the amount of light which passes through the resonance cell to the photodetector can be reduced when the resonance cell is exposed to microwaves at the hyperfine transition frequency.

To simplify the discussion, we will assume that the light from the Rb87 discharge lamp consists of just two lines corresponding to transitions from a single excited state to the split ground state. The filter cell contains Rb85 vapor which also has a split ground state and an isotopic shift (relative to Rb87) as well. An important coincidence exists: one of the lines from the Rb87 discharge corresponds one of the transitions in Rb85. This will allow us to reduce the intensity of this line by passing the Rb87 discharge light through the Rb85 vapor.

Normally, atoms in the ground state will be equally distributed between the split states, as the splitting is much less than the thermal energy of the atoms in the vapor. This distribution is modified by the filtered light from the discharge, by a process called “optical pumping”.

Suppose that the filter can completely remove one of the two discharge lines. The remaining light can be absorbed by Rb87 atoms in the resonance cell which are in the lower ground state, moving them to the upper state. When they decay from the upper state, they fall with equal probability into either ground state. As this continues, population will be moved from the lower ground state to the upper ground state, circulating through the upper state. As the population in the lower ground state is decreased, the amount of light which reaches the photodetector will increase, as the number of atoms which can absorb the radiation is reduced.

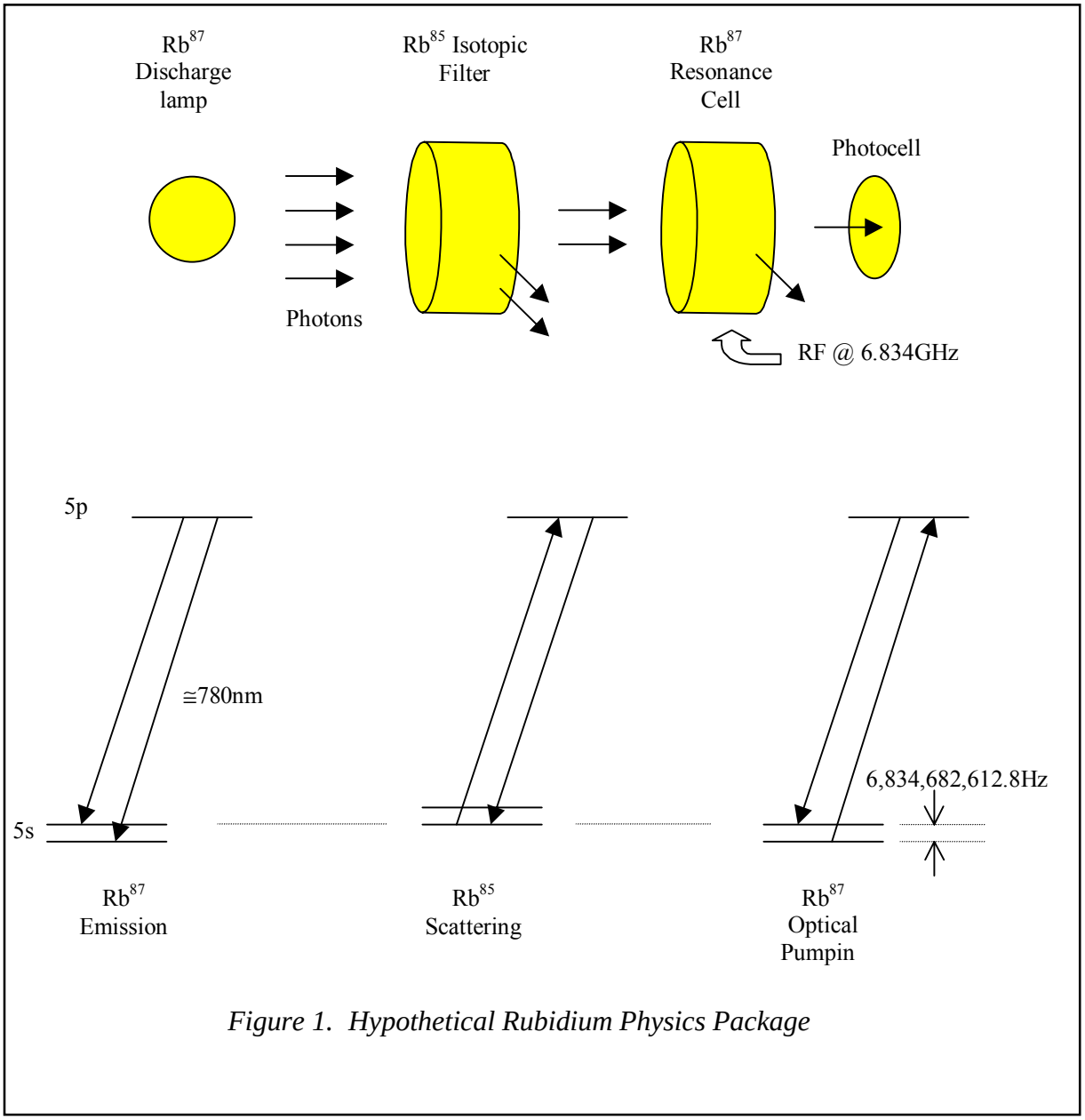

Figure 1. Hypothetical Rubidium Physics Package

Now, if we apply a microwave field at the frequency corresponding to the hyperfine transition frequency (6.834,682,612,8 GHz), the populations in the ground state will mix, and the amount of light reaching the photodetector will decrease.

The PRS10 uses the "integrated filter" topology: rather than a separate filter cell, the resonance cell contains a mixture of the two rubidium isotopes, along with a buffer gas. The lamp also contains a mixture of isotopes. The isotopic mixtures, buffer gases, and operating conditions are chosen so as to minimize temperature coefficients and intensity shifts of the apparent hyperfine transition frequency.

The apparent transition frequency will be shifted by about 3 kHz from the natural transition frequency by the buffer gas and discharge lamp spectral profile. The transition frequency differs slightly for each unit, depending on the fill pressure, etc. The transition frequency is also tuned over a few Hertz by a magnetic field which may be varied.

In the PRS10, the rubidium physics package acts as a very stable frequency detector for a frequency around 6.834 GHz. By using a microwave frequency synthesizer which is referenced to the 10 MHz OCXO, the 10 MHz may be stabilized to the rubidium hyperfine transition frequency.

PRS10 Overview

All compact rubidium frequency standards discipline a crystal oscillator to the hyperfine transition frequency in the ground state of rubidium. Several different topologies have been developed. A major difference in these designs is the method chosen to lock a standard output frequency (usually 10 MHz) to the (essentially arbitrary) hyperfine transition frequency at about 6.834 GHz.

Block Diagram

Figure 2 shows a block diagram for the PRS10 Rubidium Frequency Standard. The design of the PRS10 is quite different from other rubidium frequency standards leading to several feature and performance benefits.

Ovenized Oscillator

The output from PRS10 comes directly from a 10 MHz oven stabilized, 3rd overtone, varactor tuned, SC-cut crystal oscillator. The varactor is tuned by a 22bit digital-to-analog converter which provides a full scale tuning range of ±2 ppm. The very fine step size ($\approx 1{:}10^{-12}$) maintains the low noise inherent to the SC-cut resonator, yet the full-scale range is sufficient to compensate for crystal aging over the lifetime of the unit. This approach provides a 10 MHz output with extremely low phase noise which is virtually free of spurs.

Frequency Synthesizer

The 10 MHz also serves as the reference source to the frequency synthesizer which generates RF at about 359.72 MHz. The RF is multiplied by a factor of 19x in a step recovery diode to provide the microwave frequency (at about 6.834 GHz) which is used to interrogate the physics package. (The apparent hyperfine transition frequency varies with each physic package due to variations in buffer gas fill pressure, etc.)

The frequency synthesizer has two important characteristics: a step size of about $1{:}10^{-9}$ and very low phase noise output. The small step size is required so that only small magnetic fields will be needed to tune the apparent hyperfine transition frequency between the steps of the synthesizer. The low phase noise is required so as not to degrade the signal from the physics package, which would lead to a noisy frequency lock, and degraded output stability.

These two characteristics require a dual loop design for the frequency synthesizer. The inner loop consists of the 359.72 MHz VCO which is directly phase locked to a 3rd overtone 22.48252 MHz crystal oscillator. This loop has a large natural frequency of about 400,000r/s. The VCO's phase noise at 359.72 MHz is very close to the phase noise of the crystal (plus 24 dB for the multiplication factor of 16).

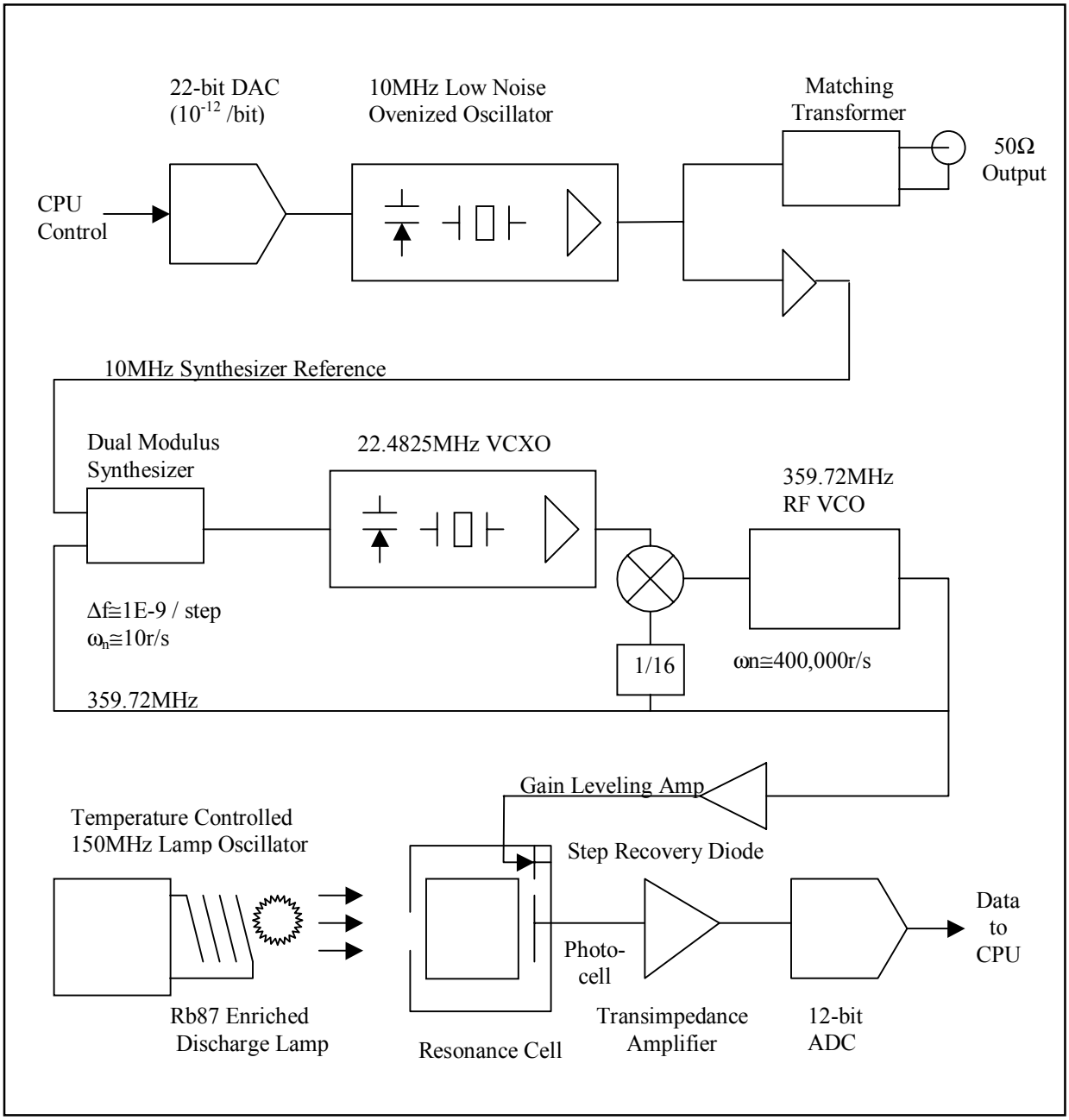

Figure 2. Rubidium Frequency Standard Block Diagram

The outer loop compares the RF frequency to the 10 MHz. This loop provides high resolution by dividing the RF and 10 MHz by large numbers, and consequently operates at a low comparison rate (typically 4 kHz). This loop has a low natural frequency (about 10 r/s) so the phase noise of the RF more than a few Hz from carrier will be determined by the inner loop. The outer loop slowly disciplines the frequency of the inner loop's crystal, keeping it locked to the 10 MHz reference.

The frequency synthesizer is set to the nearest frequency above the apparent hyperfine transition for the unit's physics package. A magnetic field is used to tune the physics package's apparent hyperfine transition frequency up to the synthesizer frequency. A 70 Hz digitally synthesized sine wave is used to phase modulate the inner loop. (The outer loop bandwidth is too small to suppress this modulation.) This generates an RF output, which when multiplied to 6.834 GHz, sweeps by about 300 Hz around the apparent hyperfine transition frequency. By sweeping through the transition at 70 Hz, the output from the photocell will have an ac component at 140 Hz, when centered on the transition. There will be an ac component at 70 Hz if we are off to one side of the transition: the phase of the 70 Hz component is used to determine if the RF is above or below the transition.

Physics Package

The physics package consists of a discharge lamp (enriched with Rb87) and an integrated filter and resonance cell. The discharge lamp operates at about 150 MHz. The lamp oscillator can provide up to 300 V_{pp} to start the lamp, which drops to about 100 V_{pp} during normal operation. The lamp oscillator voltage and current are carefully regulated to provide a consistent intensity and low noise.

The resonance cell is inside a mu-metal shell to reduce the frequency pulling effects of external magnetic fields. The apparent hyperfine transition frequency may be quadratically tuned over a range of about $\pm 2 \times 10^{-9}$ by the magnetic field coil. (The frequency shift is always positive, regardless of the direction of the magnetic field.)

To further reduce the effects of external magnetic fields, the current in the field coil is switched at 5 Hz. An external field which adds to the coil's field will increase the apparent transition frequency, and an external field which opposes the coil's field will decrease it. By alternating the coil's field and averaging, the effect of an external field can be reduced.

Control Algorithm

The microcontroller is responsible for (1) generating the 70 Hz phase modulation of the RF to probe the physics package, (2) synchronously detecting the amplitude and phase of the photosignals at 70 Hz and 140 Hz, and (3) digitally filtering the error signal to lock the 10 MHz SC-cut ovenized oscillator to the rubidium hyperfine transition.

The 70 Hz digitally synthesized phase modulation waveform is generated via a 12-bit DAC in 32 discrete steps. A low pass filter is used to remove image frequencies from the modulation waveform. The microcontroller's hardware timers are used synchronize updating of the DAC so as to eliminate sample jitter. The modulation waveform has very little distortion, noise or spurs, and is precisely 70 Hz.

The photosignal is amplified and bandpass filtered before being converted by a 12-bit ADC. The microcontroller multiplies the ADC samples by table data corresponding to sines and cosines at 70 Hz and 140 Hz. The products are summed over a frame of 14 modulation cycles

which completely eliminates signal components at 5 Hz, (and at any integer multiple of 5 Hz including 50 Hz, 60 Hz, 70 Hz and 140 Hz) from the error signal, so that there will be no spurs at the modulation frequency in the 10 MHz output.

The summed product corresponding to the detected signal at 70 Hz and 0° is used to frequency lock the 10 MHz oscillator to the Rb hyperfine transition frequency. This value is filtered in a simple, first order, IIR digital filter. The filter coefficient determines the frequency lock loop time constant. Time constants from 1 s to 128 s are available to optimize the output stability of the 10 MHz.

Initial Locking

When power is first applied to the unit, the EFC (the electronic frequency control, or, the voltage applied to the varactor in the 10 MHz SC-cut oscillator) is set to the last value for which the unit was locked. As the 10 MHz oscillator heats to its operating temperature, the output frequency will increase smoothly to converge on 10 MHz. In most cases, the output frequency will be within 0.1 Hz of 10 MHz even before the lock to rubidium is achieved.

After the lamp starts, and the physics package settles to its operating temperature, a resonance signal will be detected by the processor, and used to lock the crystal oscillator to rubidium. In the case that no signal is detected, or if the signal is lost during normal operation, the processor will suspend the frequency lock loop, and maintain the varactor voltage to the 10 MHz ovenized oscillator at a fixed level. Any of the following conditions would cause the CPU to suspend lock:

1) The detected signal at 140Hz is very low.
2) The discharge lamp light level is outside an acceptable range.
3) The RF synthesizer is unlocked.
4) The RF AGC level is pinned high or low.
5) The VXCO varactor voltage is outside the acceptable range.

Suspending lock will prevent a radical change in output frequency in the case of a physics package failure. So, in the case of most failures which cause loss of the lock to rubidium, the 10 MHz will maintain a stable output, with an aging of a few parts in 10^{10} per day.

Locking to External 1pps

The PRS10 may be locked to an external 1pps source (from a GPS or LORAN receiver, for example) by applying a 1pps pulse to the 1pps input (pin 5 on the main connector). A second order digital phase lock loop (PLL) is used to adjust the frequency of the PRS10 to match the frequency of the 1pps source over long time intervals.

The block diagram of this PLL is shown in Figure 3. The “phase detector” is the time-tagging circuit and firmware, which has a gain of K_{det} = 1bit/ns. The loop filter is a digital filter consisting of an optional pre-filter and a standard proportional-integral controller

(PI controller) with programmable proportional and integral gains. The VCO is the rubidium frequency standard, whose frequency, f, is tuned by the magnetic field via the SF command parameter with a sensitivity for its 1pps output of K_{vco} = 0.001 ns / bit-s, or (1 part in 10^{12}) / bit. The response function for each of the elements of the digital PLL is also indicated in the figure in terms of the standard Laplace variable *s*.

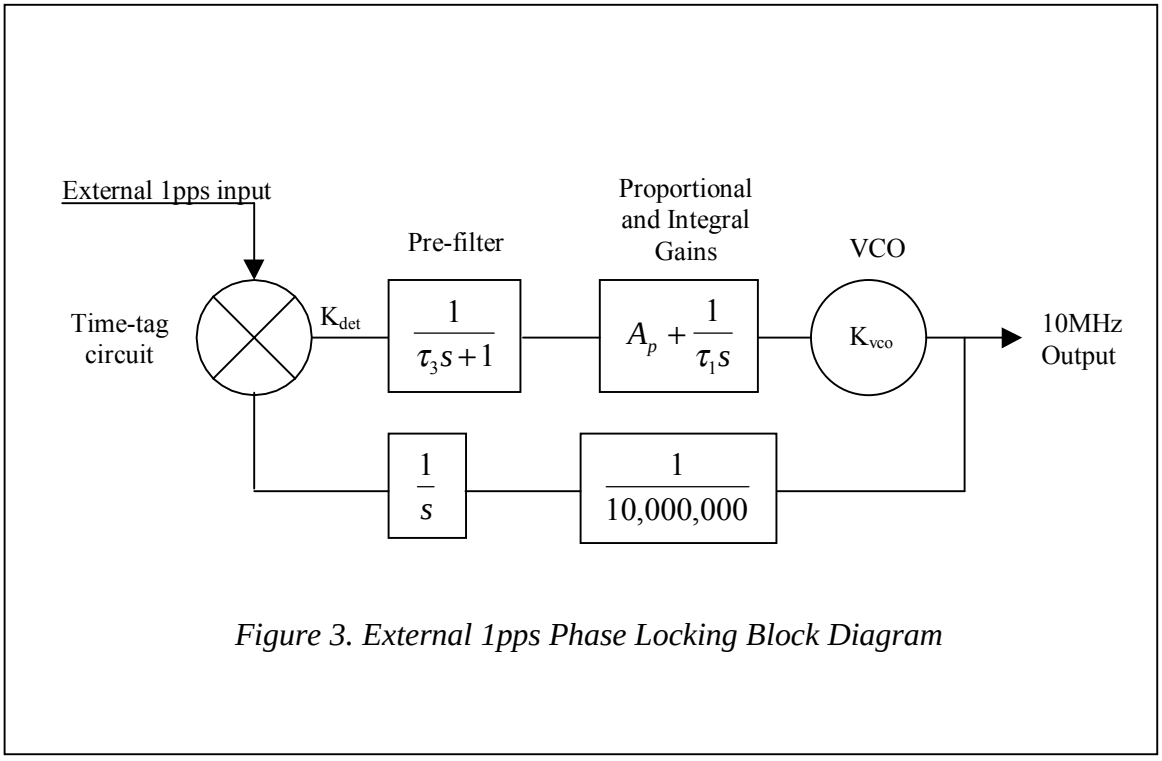

Figure 3. External 1pps Phase Locking Block Diagram

The PI controller is programmed by choosing an appropriate integrator time constant, τ_1, and a stability factor, ζ. τ_1 determines the natural time constant, τ_n, of the PLL for following a step in phase of the reference, while ζ determines the relative rise time and ringing of the PLL in response to the step. The value of ζ also represents the tradeoff in the equivalent noise bandwidth verses peaking in the passband near the natural frequency of the response function.

The PRS10 accepts integrator time constants, τ_1, ranging from 2^8 to 2^{22} seconds in powers of 2. The natural time constant is given by $\tau_n = \sqrt{\tau_1 / K_{\det} K_{vco}} = \sqrt{(1000\text{s})\tau_1}$. Thus, the PRS10 provides natural time constants ranging from 506 seconds to 18.0 hours. While the integrator time constant (τ_1) determines the natural time constant (τ_n), it is the natural time constant which characterizes the loop response.

The PRS10 accepts stability factors ranging from 0.25 to 4.0 in powers of 2. The default value of ζ = 1.0 corresponds to a critically damped response; $\zeta < 1.0$ and $\zeta > 1.0$ correspond to under-damped and over-damped responses respectively.

With τ_1 and ζ specified, the proportional gain, A_p, of the controller is given by the equation $A_p = 2\zeta / \sqrt{K_{\det} K_{vco} \tau_1} = 2\zeta / \sqrt{(0.001 s^{-1})\tau_1}$. With the default time constant, τ_1, of 65,536 seconds and a stability factor, ζ, of 1.0, the proportional gain will be about 0.25. In this case the instantaneous frequency of the rubidium source will be adjusted by about 0.25 parts in 10^{12} per nanosecond of time-tag measured.

The PRS10 also provides an optional pre-filter. The pre-filter is enabled by default, but it can be disabled by sending the command **LM0**, which puts the PRS10 into lock mode 0. When the pre-filter is enabled, the PRS10 will exponentially average the time tags output by the "phase detector" before passing the result to the PI controller. The time constant of the pre-filter, τ_3, is hard coded to be $\tau_n/6.0$ in order to obtain the maximum benefits of the averaging while simultaneously insuring that the PLL will be stable

Use of the pre-filter is recommended when locking to references that have poorer short term stability than the PRS10, but better long term stability. Locking to the 1pps output by GPS is a prime example of such a case. Use of the pre-filter dramatically reduces the digital PLL's sensitivity to the sort term jitter of 50 to 300 ns present on the GPS reference 1pps. The GPS reference also has a significant amount of 1/f noise associated with it. Very long time constants are therefore required to prevent the PRS10 from following this noise too closely. The PRS10 provides natural time constants of up to 18.0 hours, which will allow the PRS10 to follow GPS over time scales on the order of a day, but retain the superior short term stability of the rubidium clock. When locking to a reference that has short term stability comparable to the PRS10, disabling the pre-filter is recommended because it will allow the PRS10 to better track the phase of the reference.

In lock mode 0, the PRS10's digital PLL will approximate one of the following three equations depending on the value of ζ:

$$\Delta T(t) = \frac{F_0 - \zeta \Delta T(0)/\tau_n}{\sqrt{1-\zeta^2}/\tau_n} e^{\frac{-\zeta t}{\tau_n}} \sin(\sqrt{1-\zeta^2}\, t/\tau_n) + \Delta T(0) e^{\frac{-\zeta t}{\tau_n}} \cos(\sqrt{1-\zeta^2}\, t/\tau_n) \qquad \text{for } \zeta < 1$$

$$\Delta T(t) = t[F_0 - \Delta T(0)/\tau_n] e^{\frac{-t}{\tau_n}} + \Delta T(0) e^{\frac{-t}{\tau_n}} \qquad \text{for } \zeta = 1$$

$$\Delta T(t) = \frac{-\left[F_0 - (\zeta + \sqrt{\zeta^2-1})\Delta T(0)/\tau_n\right]}{2\sqrt{\zeta^2-1}/\tau_n} e^{\frac{-(\zeta+\sqrt{\zeta^2-1})t}{\tau_n}} + \frac{\left[F_0 - (\zeta - \sqrt{\zeta^2-1})\Delta T(0)/\tau_n\right]}{2\sqrt{\zeta^2-1}/\tau_n} e^{\frac{-(\zeta-\sqrt{\zeta^2-1})t}{\tau_n}} \qquad \text{for } \zeta > 1$$

ΔT(0) is the initial offset in phase of the PRS10 from the reference. F_0 is the initial offset in frequency of the PRS10 from the reference before the digital PLL is enabled. *ΔT(t)* details how the PRS10 approaches the phase of the reference as a function of time. With the default time constant, τ_1 = 65,536s, and stability factor, ζ = 1, the PRS10's 1pps output will

exponentially approach the phase of the reference 1pps input with a time constant τ_n = 8,095 seconds or approximately 2¼ hours. In lock mode 1, the equations describing *ΔT(t)* are qualitatively similar to those presented above, but generally can only be solved numerically.

The locking algorithm of the PRS10 proceeds as follows:

• The 1pps PLL is enabled when the unit is turned-on or restarted if the PL parameter stored in the unit's EEPROM is "1".

• The PLL will begin to control the frequency of the rubidium frequency standard when 256 consecutive "good" 1pps inputs (i.e., 1pps inputs which are within ±2048 ns of the first time-tag result, modulo 1 s) are received.

• After receiving 256 consecutive "good" 1pps inputs, the 1pps pulse delay is set to the last of the 256 time-tag values. (For example, if the last of the 256 "good" time tag values is 123,456,789 ns then the program will set the 1pps output delay to 123,456,789 ns, which moves the 1pps output by 123,456,789 ns, so that new time-tag values will be about zero.) Also, the current value of the SF parameter (which adjusts the frequency of the rubidium frequency standard over the range of ± 2000 parts in 10^{12}) is used to initialize the integrator, Int(0). (The current value of the SF parameter may be from the internal calibration pot position, an external calibration voltage, the value from a previously received SF command, or the value left over from a previous PLL lock.) If the pre-filter is enabled, the exponential filter for the time tags is zeroed.

• The unit will lock the frequency of the PRS10 to the "good" 1pps input pulses. "Bad" 1pps inputs (1pps inputs with time-tags greater than 1,024 ns from the last "good" 1pps input) will be rejected. The frequency parameter, f, to the SF command will be updated with each "good" time-tag result, ΔT(n), as follows:

The pre-filter : if **LM0** $\overline{\Delta T}(n+1) = \Delta T(n)$

The pre-filter : if **LM1** $\overline{\Delta T}(n+1) = (1.0 - \Delta t/\tau_3)\,\overline{\Delta T}(n) + (\Delta t / \tau_3)\,\Delta T(n)$

The integral term: $\mathrm{Int}(n+1) = \mathrm{Int}(n) - (\overline{\Delta T}(n+1) / \tau_1) K_{det} \Delta t$

The proportional term: $\mathrm{Pro}(n+1) = -A_p\,\overline{\Delta T}(n+1) K_{det}$

The frequency setting: $f(n+1) = \mathrm{Pro}(n+1) + \mathrm{Int}(n+1)$

In the above equations, Δt is the time between phase comparisons, which is one second for the PRS10. The frequency control value, f, ranges over ±2000 bits. If the new f value exceeds 2000, it is set to 2000. If the new f value is less than -2000, it is set to -2000.

If the new integral term exceeds 2000, it is set to 2000. If the new integral term is less than -2000, it is set to -2000. This will prevent "integrator wind-up" in the case that the f-value is pinned for a long time to slew the 1pps output in line with the 1pps input.

The output of the digital filter, f, is used as the frequency control parameter for the SF (set frequency) command, which is updated once a second.

• The PLL will be aborted and restarted if there are 256 consecutive "bad" 1pps inputs. (This could happen if the 1pps input is moved suddenly by more than 1,024 ns.) The PLL will also be aborted and restarted if the measured time-tag value for a "good" 1pps input exceeds ±4 ns/s * τ_1. (For τ_1's default value of 65,536 seconds, the PLL will restart if the absolute value of a "good" time-tag is greater than 262,144 ns. This could happen if the 1pps input is more than a few parts in 10^{-9} off the correct frequency for a long time.)

CPU Tasks

In addition to the frequency lock loop control, the microprocessor is responsible for a variety of other tasks. The CPU sets D/A values which control the microwave amplitude, the lamp intensity, the 10 MHz output amplitude, and set the temperature of the crystal, lamp and resonance cell. The CPU will also controls peripheral electronics to output a 1pps pulse (with 1ns placement) and measure the time for a 1pps input pulse (with 1 ns resolution).

There is an RS-232 interface which allows closed-case calibration of the PRS10. This capability may also be used to servo the 10 MHz or 1pps outputs to another frequency or time source in a system. For example, this would allow the PRS10 to be locked to the 1pps from a GPS receiver with a long time constant to eliminate aging.

PRS10 Applications

In virtually all cases, the PRS10 may be "dropped into" applications which use the Efratom FRS-C-1A8A4C (10 MHz sine output, -5°C to +65°C) or the FRS-N-1A8A4B (10 MHz sine output, -55°C to +65°C).

Some customers may wish to evaluate the PRS10 on the bench. To facilitate this, SRS can provide a connector adapter, power supply and RS-232 cable. The adapter breaks-out the Cannon plug on the PRS10 to a power connector (2.1 mm with +24 V to center pin), three BNCs (10 MHz and 1pps output and 1pps input), and a DB9 (for the RS-232). The adapter also has status indicators for power, lock and RS-232 activity. This kit allows the PRS10 to be operated from 110-240 Vac (50/60 Hz), provides for a direct connection to a PC via a serial port (typically COM2:), and allows the use of standard BNC cables.

The PRS10 may also be operated with a customer supplied connector (Cannon series DAM11W1S with coaxial insert DM53740-5008 for RG174 cable) from a bench dc power supply. The power supply should be able to supply 2.2 A at +24 Vdc.

Interface Connector

Pin	Name	Description
1	LOCK/1PPS	Lock indication and 1pps output. (See LM command)
2	POT WIPER	Ext. freq. calibration. Nom:+2.50 V. 0-5 V for $\pm 2 \times 10^{-9}$
3	POT -	Ground reference for external frequency calibration.
4	TXD/PHOTO	RS-232 data output or photo I/V monitor output
5	1PPS_IN/PHOTO	1pps input for time-tagging or photo-amp output
6	+24(HEAT)	+24 Vdc supply for discharge lamp and heaters
7	RXD/EFC	RS-232 data input or EFC monitor output
8	POT +	+5.00 Vdc reference output for external freq. cal. pot.
9	+24(CLEAN)	+24 Vdc supply for electronics (not heaters or lamp)
10	GROUND	Case ground and power supply return
coax	10MHz	10 MHz sine output on center conductor

Configuration Notes

The functions of three pins (4, 5 and 7) on the interface connector may be modified by internal hardware jumpers. The function of the LOCK output may be modified via RS-232.

Pin 1: LOCK/1PPS output. The default configuration is: +5 V indicates that the unit is not locked to rubidium (as during warm-up), 0 V indicates a successful lock of the 10 MHz oscillator to rubidium, pulsing high for 10 µs at a 1pps rate. The 1pps output may be moved earlier by any interval from 1ns to 999,999,999 ns via RS-232 command. The unit may be configured to omit the 1pps output via the LM command (via RS-232).

Pin 4: TXD/PHOTO The default configuration uses this pin as an output for RS-232 data. Many system parameters (including the lamp intensity) may be monitored via the RS-232 interface. The function of this pin may be changed to an analog monitor for the lamp intensity by removing one resistor (R347) and installing a 10 kΩ resistor for another (R348) on the microcontroller PCB.

Pin 7: RXD/EFC The default configuration uses this pin as an input for RS-232 data. Many system parameters (including the EFC, electronic frequency control) may be monitored via the RS-232 interface. The function of this pin may be changed to an analog monitor for the EFC by removing one resistor (R354) and installing a 10 kΩ resistor for another (R353) on the microcontroller PCB.

Pin 5: 1PPS_IN/PHOTO The default configuration uses this pin as a 1pps input to allow time-tagging or phase locking to an external 1pps source. The function of this pin may be changed to allow monitoring of the amplified photo-signal. When configured as a 1PPS_IN, R241 will be omitted on the top PCB, and a 1 kΩ resistor will be installed for R242. When configured for PHOTO_AMP output, R242 will be omitted on the top PCB, and a 1 kΩ resistor will be installed for R241.

10 MHz coax shield The default configuration floats the shield of the 10 MHz coaxial connector with respect to ground. The 10 MHz output is transformer coupled, and the shield may be ground referenced by installing the jumper between J101 and J102 (located near the connector on the 10 MHz oscillator PCB.)

Hardware Notes

All of the pins on the interface connector are protected against continuous connection to any potential up to 24 V_{dc}. The power supply pins are protected against polarity reversal and may be operated up to +30 V_{dc}. In most applications, both +24 V_{dc} supplies (heater and electronic supplies) will be connected together and operated from a +24 V_{dc} supply.

Logic outputs (LOCK/1PPS and TXD/PHOTO) have a 1 kΩ output resistance driven by a CMOS logic device operating between +5 V_{dc} and ground. Logic inputs (RXD/EFC and 1PPS_IN) have 100 kΩ to ground and 3.9 kΩ CMOS gate inputs (which have input protection diodes to +5 V and ground).

RS-232 data is sent to the host on pin 4, received from the host on pin 7. The baud rate is fixed at 9600 baud, 8 bits, no parity, with 1 start and 2 stop bits. No DTR or CTS controls are used; rather, the XON/XOFF protocol has been implemented. The transmit drive level is 0 and 5 V, not the +/-12 V normally associated with RS-232. These levels are compatible with most RS-232 line receivers, but does not require their use (a TTL inverter may be used instead), hence simplifies the interface when used inside an instrument at the sacrifice of degraded noise immunity over long lines.

The PRS10 may be connected directly to a PC's COM2: port with three wires: TXD, RXD, and ground. As the PRS10 sources only +5/0 V for the RS-232 (via 1 kΩ) the connecting cable should be kept short.

PRS10	PC's COM: (DB9 Connector)	PC's COM: (DB25 Connector)
Pin 7 (RXD)	Pin 3 (TXD)	Pin 3 (TXD)
Pin 4 (TXD)	Pin 2 (RXD)	Pin 2 (RXD)
Pin 10 (GND)	Pin 5 (GND)	Pin 7 (GND)

Operating Temperature

The unit should be operated so that the baseplate temperature stays below +65 °C. This requirement is usually met by units operating on the bench at room temperature when powered by +24 V_{dc}.

Frequency Adjustment

A magnetic field coil inside the resonance cell is used to tune the hyperfine transition frequency. The magnetic field is controlled by a 12-bit DAC. The output frequency (at 10MHz) tunes quadratically with the DAC setting ($0 \le DAC \le 4095$), and $\Delta f(Hz) \approx 5x10^{-9} \times DAC^2$. The DAC setting is changed from the nominal calibration value (see MO command) in various ways, including, calibration pot position, external calibration voltage, direct setting (see SF command), and external 1pps PLL control.

When the unit is first turned on (or restarted), the internal frequency calibration pot position will be used to set the DAC relative to the calibration value stored in EEPROM. (If a voltage is applied to pin 2 of J100 (POT_W) then this voltage will override the pot position.) An SF command may be sent, or a 1pps input may be applied, to control the frequency offset directly. If either the SF command or the 1pps input control the frequency offset, then the pot position (or external control voltage) will not be used again until the power is cycled or the unit is restarted. All the various ways to adjust the frequency of the 10 MHz output are linearized, and they have a span of $\pm 2000 \times 10^{-12}$ or ±0.020 Hz.

RS-232 Instruction Set

Syntax

Commands consist of a two letter mnemonic and one or more parameters. Commands which end with a question mark (?) will return a value. Commands which end with an exclamation point (!) write the current parameter value to EEPROM for use after the next restart. Commands which end in an exclamation point and a question mark (!?) return the value stored in EEPROM.

All data is communicated in ASCII codes. Commands are case insensitive, and spaces (ASCII 32_{10}) are ignored. Commands are processed when a carriage return (ASCII13_{10}) is received. Returned values are delimited with commas (in the case of multiple returned values) or a carriage return (in the case of a single or the last returned value). Commands available to the end user are in **bold**: some commands are for factory use only and a special code must be transmitted to enable these commands. Parameter lists are enclosed in curly brackets { }, the brackets are not part of the command.

On reset, the unit will transmit the characters: PRS_10 with a carriage return.

Initialization

RS 1

Restart. This command will restart the PRS10's microcontroller just like power-on. (It is not necessary to send a **RS** command on power-up.) All values will return to the values stored in EEPROM. (verbose mode disabled, 10 MHz set to last stored value, etc.) The frequency lock-loop will be disabled until the microcontroller verifies that the unit is warmed-up and that a useful signal level is present. Example**: RS 1** will cause the unit to restart.

VB{0 or 1}
VB?

Set verbose mode. The verbose mode is useful when a human is communicating with the PRS10 using a terminal program (the PRS10 will provide an "OK", command prompts, etc.) The verbose mode should be disabled when a computer program is communicating with the PRS10 (where format characters would interfere.) **Examples: VB0** disables the verbose mode (this is the power-on default mode.) **VB1** will enable the verbose mode.

ID?

Identify. This command returns an identification string which includes the serial number and firmware version of the PRS10. **Example: ID?** will return the identification string PRS10_3.15_SN_12345 (model _firmware version_serial-number).

SN?
SN{value}
SN!
SN!?

Serial number. This command returns the unit's serial number. **Example: SN?** will return 21567 for a unit with serial number 21567. The command to write and burn a serial number are for factory use only.

ST?

Status. This command will return a six number string corresponding to the values of the six status bytes. Each number will range between 0 and 255, and will be separated by commas. (For definitions of the status bytes, refer to the end of the detailed command descriptions.)

LM{value} value = 0, 1, 2, or 3
LM?
LM!
LM!?

Lock mode pin configuration. This command is used to configure the LOCK/1PPS output (pin 1 on the main connector, J100.) The LOCK/1PPS pin may be configured per the following table:

LM	Description of LOCK/1pps Output
0	Output goes low when locked to Rb, pulses high for 10 µs at 1 Hz 1pps locking pre-filter disabled
1	Output goes low when locked to Rb, pulses high for 10 µs at 1 Hz 1pps locking pre-filter enabled (default)
2	Output goes low when locked to Rb, 1pps is disabled
3	Output goes high when locked to Rb, 1pps is disabled

The default value is 1, so that pin 1 will go low when the unit is locked to rubidium, and will pulse high for 10 µs at a 1 Hz rate. The position of the 1pps pulse may be moved with the PP command. **Example: LM?** Could return 1, indicating that the unit is in its default configuration so that the lock pin goes low when locked to Rb, pulsing high for 10 µs at a 1 Hz rate. To configure the unit for no 1pps output, the command string **LM 2** followed by **LM !** will change the unit's power on default for no 1pps output.

RC 1
RC!

Recall. This command is used to return all values in EEPROM to the values which were present when the unit was first shipped from the factory (except for the unit-start and lamp-start counters.) This command should be used if you have been writing values to EEPROM and have somehow corrupted the operation of the device. Executing this command may require calibration of the unit, as the frequency calibration values are also returned to their factory values. The unit will be restarted after the values in EEPROM have been restored to their factory values. **Example: RC 1** will return all calibration values to the values which were determined for the unit when it was manufactured and restart the unit. The RC! command is a factory-only command which writes all of the current parameter values to the EEPROM.

Frequency Lock-loop Parameters

LO{value} value = 0 or 1
LO?

Lock. This command can be used to stop the frequency lock-loop (FLL). It is essentially the same as setting the gain parameter to zero. It may be desirable in a particular application to stop the FLL and set the frequency control value for the 10MHz oscillator manually. (See the FC command.) **Example: LO 0** will stop the FLL. **LO?** will return a value of 0 (if the FLL is not active) or 1 (if the FLL is active.)

FC?
FC{high,low} $0 \le high \le 4095$ $1024 \le low \le 3072$
FC!
FC!?

Frequency control. These commands allow direct control of the 22bit value which controls the frequency of the 10 MHz ovenized oscillator. Normally, this value is controlled by the FLL control algorithm, however, the FLL may be stopped, and the value adjusted manually. (See the LO command.)

Two 12-bit DACs are scaled (by 1000:1) and summed to provide a varactor voltage which controls the frequency of the 10 MHz oscillator. The low DAC, which operates over half its range (to avoid FFL oscillations at the roll-over to the high DAC) provides a LSB frequency resolution of $1.5{:}10^{-12}$. The high DAC, which has a nominal value of 2048, has a LBS resolution of $1.5{:}10^{-9}$. These DACs provide a total tuning range of about ±3 ppm.

Example: Suppose a unit's FLL has been operating for some time and has settled. An **FC?** will return the current value of the DAC pair which might be 2021,1654. (Tracking the FC value over a long period of time tells you about the frequency variations of the 10MHz

crystal. The FC values will change to correct for variations in the crystal frequency due to aging and ambient conditions.)

Both DACs may be set to any value in the range specified above. **Example: FC 2048,2048** will set the 10MHz oscillator back to the middle of its tuning range. However, it is possible to set the frequency of the 10 MHz oscillator so far from the correct frequency that the FLL signal disappears, making the lock impossible. If this happens, the last saved FC value may be read from EEPROM with the **FC!?** command and restored with the **FC{high,low}** command.

The **FC!** command is used to save the current FC values in the unit's EEPROM. The **FC!?** Command may be used to read the value which is stored in the EEPROM. The value stored in EEPROM is used to set the 10 MHz at startup, before the FLL can be established. Occasionally while the unit is operating (at about 20 minutes after power-on and once a day there after) the program will write a new value to EEPROM to correct the value for crystal aging. **Example: FC!?** will return four values (separated by commas), the number of power cycles the unit has undergone, the number of times the FC pair has been written to EEPROM, and the value of the FC pair (high, low) which is used at turn-on and restart.

DS?

Detected signals. This command returns two numbers corresponding to the synchronously detected signals at the modulation frequency, ω_{mod}, and at twice the modulation frequency, $2\omega_{mod}$.

The first number, the amplitude of the signal at ω_{mod}, is the error signal in the rubidium frequency lock loop. The value is proportional to the instantaneous frequency error of the 10 MHz oscillator as detected by the physics package. The value may be large when the unit is first locking, and will bobble around zero in steady state. Each LSB corresponds to about 15 μVrms of signal at ω_{mod}.

The second number is the amplitude (in millivolts rms) of the synchronously detected signal at twice the modulation frequency, $2\omega_{mod}$. The amplitude of this signal is proportional to the strength of the rubidium hyperfine transition signal.

The returned value is a spot measurement taken over just one cycle of the modulation frequency. Since the signals have several Hz of equivalent noise bandwidth, they will be rather noisy.

Example: DS? could return 55,800 indicating a small error signal and a strong resonance signal.

SF{value} -2000 ≤ value ≤ +2000
SF?

Set frequency. This command is used to override the internal calibration pot (or external calibration voltage) to set the frequency directly, relative to the calibration values in EEPROM (see the SP and MO commands.) The command sets the frequency offset in units of parts in 10^{-12} (corresponding to a frequency resolution of 10 μHz at 10 MHz.) The SF? command will return the currently set relative frequency value (with a range of ±2000) whether the value comes from the internal calibration pot position, an external frequency control voltage, an SF command, or from the external 1pps phase lock loop control algorithm. However, SF set command is ignored if the unit is phase-locked to an external 1pps signal. (To re-establish direct control via the SF command, the PLL must be disabled. See PL 0 command.)

Example: SF 100 will set the frequency 100 x 10^{-12} (or 0.001 Hz) above the stored calibration value, and the **SF?** command will return 100.

Data from the SF command cannot be saved when the power is turned off. (To do this type of calibration, see the SP and MO commands.) Once executed, the SF command will disable the analog channels (internal calibration pot and external calibration voltage) until the power is cycled or the unit is restarted.

SS?
SS{value} 1000 ≤ value ≤ 1900
SS!
SS!?

Set slope. This command is used to read the slope calibration parameter for the SF command. This parameter compensates for a variety of factors which affect the magnitude of the coefficient between magnetic coil current and transition frequency. **Example: SS?** might return 1450, the nominal parameter value. This calibration parameter may not be altered by the end user.

The (factory only) SS! command is used to store the current value of the SS parameter to the unit's EEPROM. The SS!? will return the value of the SS parameter which is used on power-up or restart.

GA?
GA{value} 0≤ value ≤ 10
GA!
GA!?

Gain. This command sets the gain parameter in the frequency lock-loop algorithm. Higher frequency lock-loop to remove 67% of the frequency error) but have larger equivalent noise bandwidths (which will reduce the short-term stability of the 10 MHz output.) A gain of 0

will stop the frequency lock-loop so that the frequency of the output is determined by the 10MHz ovenized oscillator alone. The gain setting, approximate time constants, and approximate equivalent noise bandwidths are detailed in the following table. The gain parameter is set automatically by the program, however, the user may want control over the parameter in special circumstances. **Example: GA7** will set the gain parameter to 7, which has a time constant of about 2 s, which is a typical value for normal operation. **GA?** could return a value of 8 just after restart, which has a short time constant of about 1 s to assist the initial frequency locking. Setting the gain parameter during the first 6 minutes after turn-on or restart will abort the automatic gain sequencing.

Command	Time Constant (seconds)	Noise Bandwidth (Hz)
GA 0	Infinite	0
GA 1	128	0.002
GA 2	64	0.004
GA 3	32	0.008
GA 4	16	0.016
GA 5	8	0.032
GA 6	4	0.064
GA 7	2	0.128
GA 8	1	0.256
GA 9	0.5	0.512
GA 10	0.25	1.024

The **GA!** command stores the current value of the frequency lock loop gain parameter into the unit's EEPROM. **Example:** If the current value of the gain is 6, the command **GA!** will write 6 to the unit's EEPROM which will be used to initialize the gain parameter after the next power-on or restart. Then **GA!?** will return a 6.

PH?
PH{value} 0≤ value ≤ 31
PH!
PH!?

Phase. This command is used to set the phase of the synchronous detection algorithm. The frequency lock-loop (FLL) uses the in-phase component of the photo-signal at the modulation frequency (70 Hz) as the error signal for the FLL. The phase between modulation source and the error signal is affected by phase shifts in the modulation and signal filters and by optical pumping time constants. This parameter corrects for the accumulation of all of these phase shifts. Each modulation cycle consists of 32 phase slots, so each phase increment corresponds to 11.25°. **Example: PH?** would typically return a value of 24.
The PH! command is used to write the current phase parameter into the unit's EEPROM. This is a factory only command. The value which is burned in EEPROM is used on power-on

and restart, and may be queried by the **PH!?** command. **Example: PH!?** could return a typical value of 24.

Frequency Synthesizer Control

A frequency synthesizer, which uses the 10 MHz OCXO as a frequency reference, is used to generate the RF which sweeps the rubidium hyperfine transition. The frequency synthesizer multiplies the 10 MHz by a factor M = 19 * (64*N + A) / R, to generate a frequency near 6.834 GHz. (The factor of 19 is from frequency multiplication in the step recovery diode, and the other terms come from the operation of the dual modulus frequency synthesizer integrated circuit.)

The apparent transition frequency is different for each physics package, due mostly to variations in the fill pressure of the resonance cell. The frequency synthesizer parameters, R, N and A, are used to adjust the frequency synthesizer's output frequency to the closest frequency just above the apparent transition frequency, then the magnetic field is set to move the transition frequency up to the synthesizer frequency.

During frequency locking, the frequency of the 10 MHz OCXO is adjusted to maintain the output of the frequency synthesizer on the rubidium hyperfine transition frequency. Initial calibration of the unit will involve finding the synthesizer parameters and magnetic field value which will lock the 10 MHz OCXO at exactly 10 MHz.

During the lifetime of the unit, there will be some aging of the physics package, which will cause the apparent transition frequency to change. This is usually corrected by minor calibration adjustments of the magnetic field strength, which provides a setting resolution of a few parts in 10^{-12}. (See the MO command.) However, if the magnetic field strength reaches its lower or upper limit, it is necessary to change the frequency synthesizer parameters, which can change the output frequency in steps of about one part in 10^{-9}.

The table in Appendix A details the values for R, N and A for the range of frequencies needed.

SP?
SP {R,N,A} $1500 \leq R \leq 8191$ $800 \leq N \leq 4095$ $0 \leq A \leq 63$
SP!
SP!?

Set Parameters. This command is used to set or query the frequency synthesizer's parameters, which will coarsely adjust the unit's output frequency. These parameters may need to be adjusted if the unit cannot be calibrated by magnetic field adjustment.

Example: During calibration, a unit's 10 MHz output frequency is found to be low by 0.010 Hz, and the magnetic field offset adjustment is already at its maximum. (See the MO

command.) Sending the **SP?** command returns the current values of R, N and A which are 2610,1466,63 in this example. This corresponds to line 38 in the table in Appendix A. To *increase* the frequency of the 10 MHz output, we select the next *higher* setting, line 37, which will *increase* the frequency by 0.01986 Hz. To do this, we send the command **SP 5363,3014,22** (which are the parameters from line 37). Waiting for the frequency to settle, we now measure the output to be about 0.0098 Hz high. Now the magnetic field is adjusted down to calibrate the unit to exactly 10 MHz. (The **SP!** command is used to save these new values in EEPROM for the next power-on or restart. Also see the MO command for adjusting the magnetic field.)

The **SP!** command is used to write the current frequency synthesizer parameters to the unit's EEPROM for use after the nest restart or power-on cycle. This command is used after the SP command is used during the calibration of the unit. **Example: SP!** will write the frequency synthesizer parameters (R, N and A) which are currently in use to the unit's EEPROM. **SP!?** will return the values for R, N and A which are currently in the unit's EEPROM. The **SP!?** command may be used to verify that the **SP!** write command executed correctly.

Magnetic field Control

A magnetic field coil inside the resonance cell is used to tune the apparent hyperfine transition frequency. The magnetic field is controlled by a 12-bit DAC. Increasing the magnetic field will increase the hyperfine transition frequency, which will increase the frequency of the 10 MHz output. The transition frequency may be tuned over about $\pm 3 \times 10^{-9}$ by the magnetic field, which corresponds to ±0.030 Hz at 10 MHz. The output frequency (at 10 MHz) tunes quadratically with field strength, and $\Delta f(\text{Hz}) \approx 0.08 * (\text{DAC}/4096)^2$.

A minimum magnetic field should always be present to avoid locking to the wrong Zeeman component of the hyperfine transition, so the 12-bit DAC may be set from 1000 to 4095 with 3000 being the nominal midscale value. (A DAC value of 1000 corresponds to about 6% of the full-scale frequency tuning range, 3000 corresponds to about 53%, while 4095 is 100% of the full-scale range.)

To help cancel frequency shifts due to external magnetic fields, the current in the coil is switched at a 5 Hz rate. The frequency lock-loop averages over a full period of the switch rate to avoid injecting a spur at 5 Hz onto the 10 MHz control signal. The switching of the magnetic field is enabled at power-on and restart, but may be turned on or off by RS-232 command. (see MS command.)

The commands associated with magnetic field control (MO, MS, and MR) allow direct control of the magnetic field circuitry. Most users will not want to control the magnetic field directly, but will instead allow the program to read the frequency calibration pot or external control voltage and then control the magnetic field. If they want software control of the unit's calibration, they may choose to use the SF commands, which disable the analog control and

allow the frequency to be adjusted over a range of $\pm 2000 \times 10^{-12}$. (The program will linearize the magnetic field control of the frequency offset with either analog or software control.)

MS?
MS{0 or 1}

Magnetic switching. The MS command is used to turn off or on the 5Hz switching of the frequency tuning magnetic field. Magnetic switching is enabled when the unit is powered-on or after a restart. (Since the PRS10 is calibrated with the field switching enabled, turning off the field switching may alter the calibration.) **Example: MS 1** will turn on the magnetic field switching, and **MS 0** will turn it off. **MS?** will return a "1" if the field switching is currently enabled.

MO?
MO{value} $2300 \leq \text{value} \leq 3600$
MO!
MO!?

Magnetic offset. The magnetic offset is the value, determined when the unit is calibrated, which calibrates the unit to 10 MHz. The restricted range is necessary to allow room for user calibration via the internal frequency calibration pot or by an external voltage. If the unit cannot be calibrated to 10 MHz within the allowed range of MO values, then a different setting for the frequency synthesizer is required. (See SP command and the table in Appendix A. **Example: MO 3000** sets the magnetic offset to 3000, which is its nominal (mid-linear scale) value. The **MO?** command reads back the current value of the magnetic offset. **MO!** is used to store the current value of the magnetic offset parameter to EEPROM for use after the next restart. **MO!?** may be used to query the value stored in EEPROM. This value is used on power-up or restarts.

MR?

Magnetic read. This command returns the value that the 12-bit DAC is using to control the magnetic field. This value is computed from the magnetic offset value (see MO command) and the position of the internal frequency calibration pot, external calibration voltage, or value sent by the SF command.

The value is computed from the equation $DAC = \sqrt{(SF*SLOPE + MO^2)}$ where SF is the desired frequency offset in parts per 10^{-12} (from the cal pot position, the SF command, or the 1pps PLL and is in the range $-2000 < SF < 2000$), SLOPE is the SF calibration factor with a nominal value of 1450 (see SS command), and MO is the magnetic offset value. The returned value should be in the range of 1000 to 4095.

Example: MR? would return a value of 3450 if the magnetic offset is at 3000, the SF command requested an offset of $+2000 \times 10^{-12}$, and the SS CAL factor has the nominal value of 1450.

Frequency Control

The frequency of the 10 MHz output may be adjusted in a number of ways: the internal calibration potentiometer may be set (accessible via a hole in the bottom plate), an external voltage (0 to +5.00 Vdc, applied to the interface connector pin 2) can override the internal pot, or, these analog channels may be overridden with a software command which sets the frequency directly.

When the unit turns on, or after a restart command, the control program will default to reading the analog channel for frequency calibration. (This is important to maintain compatibility with existing sockets.) The calibration pot and the external voltage control provide a full-scale tuning range of $\pm$ 2000 x 10^{-12}, with a worst case resolution of 5 x 10^{-12}.

All of the channels for calibrating the unit are linearized, so that the frequency characteristic will be linear with applied voltage, pot setting, or SF value even though the transition frequency changes quadratically with field strength.

One pulse per second (1pps) control

To facilitate system integration, the PRS10 provides a 1pps output which may be set over an interval from 0 to 999,999,999 ns with 1ns resolution. The unit also has the ability to measure the arrival time of a 1pps input over the same interval and with the same resolution.

The ability to time-tag a 1pps input allows the PRS10 to be phase-locked to other clock sources (such as the 1pps output from a GPS receiver) with very long time-constants. This is a very useful feature for network synchronization, and allows the configuration of a reliable Stratum I source at a very low cost.

TT?

Time-tag. This command returns the value of the most recent time-tag result in units of nanoseconds. If a new time-tag value is not available then -1 (the only case for which the returned value is negative) will be returned. **Example: TT?** would return the value 123456789 to indicate that the most recent 1pps input arrived 123,456,789ns after the 1pps output. Returned values range from 0 to 999999999.

TS?
TS{value} $7000 \leq value \leq 25000$
TS!
TS!?

Time slope. This command is used to calibrate the analog portion of the time-tagging circuit. The analog portion is used to digitize the time of arrival with 1 ns resolution and 400 ns full-scale. (Counters are used for the portion of a time interval longer than 400 ns.) The analog

circuit stretches the time interval between the 1pps input and the next edge of a internal 2.5 MHz clock by a factor of about 2000, and measures the duration of the stretched pulse by counting a 2.5 MHz clock. The analog portion of the time-tag result is calculated from the equation $\Delta T(ns) = counts * TS / 2^{16}$, where TS is the time slope value, which has a nominal value of 13,107.

Example: TS? might return 14,158 which is a time slope parameter value a bit above the nominal value, which would be required if the analog portion of the time-tagging circuit stretched the pulse by a bit less than a factor of 2000. **TS?** will return the current value of the time slope.

The TS! command is used to write the current value of the time slope parameter into the unit's EEPROM. The TS {value} and TS! are factory only commands. Example: TS! will write the current value of the time slope (which may be queried with the TS? command) to the unit's EEPROM. **TS!?** will return the time slope calibration factor which is in the unit's EEPROM.

TO?
TO{value} $-32767 \leq value \leq 32768$
TO!
TO!?

Time offset. This calibration value (in ns) is added to the measured time-tag value to reference the result to the 1pps output. To calibrate, the 1pps output is connected to the 1pps input and the time-tag is read with the TT? command. The returned value is subtracted from the current TO value and sent with the TO command to calibrate the offset.

Example: Suppose: the 1pps output is connected to the 1pps input. A time tag value, read with the TT? query, returns a value of 25ns. The TO parameter, read via the TO? query, returns a value of -1750ns. The command TO -1775 is sent to correct for the offset. After waiting about one second (to allow another time-tag value to be acquired) the next TT? query returns a value of 2ns (indicating a measurement of 2ns after the 1pps output) Waiting another second, the next TT? query returns the value 999,999,999ns (indicating 1 ns before the 1pps output). These values are consistent with a well calibrated time-tag offset.

Following calibration of the TO parameter, the **TO!** command is used to write the current value of the time offset to the unit's EEPROM. Example: **TO!** will write the current time-tag offset value to the unit's EEPROM for use after the next power-up cycle or restart command. **TO!?** will return the value which is burned in the unit's EEPROM. (Note: Firmware revisions prior to Rev 3.32 do not allow user TO! commands. Check the firmware revision with the ID? command.

PP{value} $0 \leq value \leq 999999999$

Place pulse. This command is used to move the 1pps output from its current position. The 1pps output can be moved earlier in time by 1 ns to 999999999 ns. Since the 1pps input time-tag is referenced to the 1pps output, changing the 1pps output placement will change the report time-tag values as well. (See the TT and TO commands.) **Example: PP 123456789** will move the 1pps pulse train earlier by 123,456,789 ns.

PS?
PS{value} $100 \leq value \leq 255$
PS!
PS!?

Pulse slope calibration. This command is used to calibrate the analog portion of the 1pps output time delay circuit. This circuit is used to delay the 1pps pulse train with 1 ns resolution and 100 ns full-scale. (Counting logic is used for the portion of the time interval longer than 100 ns.) The pulse slope value corresponds to the DAC8 value which provides a delay closest to (but not exceeding) 100 ns. Example: PS 200 set the pulse slope to its nominal value of 200. (PS{value} is a factory only command.) The **PS?** command will return the current value of the pulse slope.

The PS! command writes the current value of the pulse slope to the unit's EEPROM for use after the next power-on or restart. This command is used after the pulse output analog output is calibrated. Example: PS! will write the current value of the pulse slope (which calibrates the 100 ns analog delay portion of the 1pps pulse delay circuit) to the unit's EEPROM. Note that PS! is a factory-only command.

1PPS Locking Control

To facilitate integration into systems which require very low aging, automatic calibration, or a traceable frequency standard, the PRS10 may be locked to an external 1pps input.

A second-order digital PLL is used to lock the unit's frequency (both the 10 MHz and 1pps outputs) to an external 1pps input with time constants ranging from 256 s to 65536s (about 4 minutes to about 18 hours).

When provided with an accurate and stable 1pps source, the unit will automatically align its 1pps output to the 1pps input and then adjust the frequency of the rubidium reference to maintain the alignment over time. A typical application would lock the PRS10 to the 1pps output from a GPS receiver with a time constant of several hours.

Several commands and one status byte may be used to control and monitor the PLL, however, default values will allow units to lock to clean 1pps inputs without any software interaction.

PL?
PL{0 or 1}
PL!
PL!?

Phase lock control. This command may be used to disable the 1pps PLL, or to re-enable (and so restart) the 1pps PLL. The unit is shipped with the phase lock control enabled. This command would be used if the 1pps time-tagging were being used to measure the position of 1pps inputs and phase locking is not desired. **Example: PL 0** will disable the PLL to the 1pps inputs so that the frequency of the rubidium standard will not be affected by the 1pps inputs. **PL?** will return a "1" if the PLL to the 1pps is enabled. **PL!** is used to write the current value (0 or 1) to the EEPROM for use after the next start up. **PL!?** is used to query the value of the phase lock control parameter which is stored in the unit's EEPROM.

PT?
PT{value} $0 \le \text{value} \le 14$; $\tau_1 = 2^{(\text{value}+8)}$ seconds (256, 512, ... 4,194,304)
PT!
PT!?

Phase-lock integrator time constant. This command is used to set the PLL's integrator's time constant, τ_1, which phase-locks the PRS10 to an external 1pps input. The integrator time constant is equal to $2^{(\text{value}+8)}$ seconds. The default value is 8, which provides an integrator time constant of $2^{(8+8)}$ or 65536 seconds. Integrator's time constants can range from 256 to 4,194,304 seconds, or from about 4 minutes to 18 days. It is important to note that the natural time constant, τ_n, is different from the integrator time constant, as shown in the table below. The natural time constant is the best measure of the loop response. The PLL natural time constant spans between 8 minutes and 18 hours for PT values between 0 and 14.

Example: PT10 sets the integrator time constant to $2^{(10+8)}$ seconds, or about 72 hours. (Refer to Table below.) For PT10 the natural time constant is about 4.5 hours. **PT?** will return the current value of the time constant parameter. A phase lock time constant may be stored in EEPROM as a new default with the **PT!** command. The **PT!?** command may be used to verify the value stored in EEPROM.

The following case will illustrate the operation of the PLL: Suppose that the PRS10 has been phase locked to a stable 1pps reference for a very long time (several periods of τ_n) when the 1pps reference input makes an abrupt shift of +100ns (moving later in time). The PRS10's 1pps PLL algorithm will reduce the PRS10's frequency of operation (by adjusting its SF parameter) to eliminate the 100ns phase shift between the 1pps reference input and the 1pps output. After the phase shift is eliminated, the PRS10 will settle to the "correct" operating frequency.

The PLL algorithm computes integral and proportional terms from time-tag measurements, adjusting the SF parameter to phase lock the 1pps output to the 1pps input. The table below shows the integral and proportional gain terms. For the nominal PT value of 8, the integral

term is -0.055 SF bits per hour per ns of time-tag and the proportional gain is -0.25 SF bits per ns of time-tag.

Per the table below for PT8, if the input reference shifts by +100ns, the proportional term will adjust the SF by -0.25bits/ns * 100ns = -25 bits. Each SF bit corresponds to $1:10^{-12}$ of the operating frequency, and so the PRS10 frequency will be shifted by about -25×10^{-12}. The integral term will begin ramping by (-0.055bits/hour/ns) * 100ns, or by -5.5 bits per hour. The phase shift between the 1pps input and 1pps output will be gradually eliminated.

(Phase jumps of 100ns are quite common on 1pps outputs from GPS receivers, which are a likely 1pps reference to the PRS10. The corresponding frequency jumps of 25×10^{-12} may be excessive in some applications, and so a digital pre-filter is used to smooth the time-tag values before they are used by the PLL algorithm. See LM command.)

PLL Table for all PT values, assuming a stability factor, ζ=1.

PT Parameter Parameter set by PT command	Integrator Time-Constant (hours)	Integral Gain (SF bits per hour per ns of time-tag)	Proportional Gain (SF bits per ns of time-tag)	Natural Time-Constant Characterizes PLL response (hours)
0	0.07	-14.063	-3.95	0.14
1	0.14	-7.031	-2.80	0.20
2	0.28	-3.516	-1.98	0.28
3	0.57	-1.758	-1.40	0.40
4	1.14	-0.879	-0.99	0.56
5	2.28	-0.439	-0.70	0.80
6	4.55	-0.220	-0.49	1.12
7	9.10	-0.110	-0.35	1.59
8	18.20	-0.055	-0.25	2.25
9	36.41	-0.027	-0.17	3.18
10	72.82	-0.014	-0.12	4.50
11	145.64	-0.007	-0.09	6.36
12	291.27	-0.003	-0.06	8.99
13	582.54	-0.002	-0.04	12.72
14	1,165.08	-0.001	-0.03	17.99

PF?
PF{value} $0 \leq$ value ≤ 4 ; (value:ζ) : (0:1/4, 1:1/2, 2:1, 3:2, or 4:4)
PF!
PF!?

Phase-lock stability factor. This command is used to set the stability factor, ζ, of the 1pps PLL. The stability factor is equal to $2^{(value-2)}$. The default value is 2, which provides a stability

factor of $2^{(2-2)} = 2^0 = 1$. Stability factors can range from 0.25 to 4.0. **Example: PF 1** sets the stability factor to 0.5, which will reduce the equivalent noise bandwidth of the PLL at the cost of increasing the ringing near the natural frequency (relative to the default settings). **PF?** will return the current value of the stability factor parameter. **PF!** may be used to write the current stability factor to the EEPROM for use as the new default. **PF!?** may be used to read the value of the stability factor which is stored in EEPROM.

PI?
PI {value} $-2000 \leq \text{value} \leq 2000$

Phase-lock integrator. This command is used to set the value of the integral term in the PLL's digital filter. It is not necessary to set this value, as it will be initialized by the PLL routine to the current frequency setting parameter when the PLL begins. Users may want access to the value to alter the PLL characteristics, or to investigate its operation. **Example: PI 0** will set the integrator in the PLL's digital filter to 0, which is the center of the ±2000 bit range. **PI?** will return the current value of the PLL integrator. (There are two terms which control the phase locking of the PRS10 to an external 1pps source: the integral term and the proportional term. The proportional term is equal to the value returned by an **SF?** minus the value returned by the **PI?**.)

Analog Control

SD{port}?
SD{port,value} $0 \leq \text{port} \leq 7$ and $0 \leq \text{value} \leq 255$ (factory only)
SD{port}!
SD{port}!?

Set DAC. This command is used to set (or read the settings of) an octal 8bit DAC which provides analog signals to control systems parameters. The command which sets values is only available to the factory. The command to query values may be used by all. The query command returns a single integer in the range of 0 to 255.

Port	Function
0	Controls the amplitude of the RF to multiplier in resonance cell
1	Controls the analog portion (0 to 99 ns) of the delay for the 1pps output
2	Controls the drain voltage for the discharge lamp's FET oscillator
3	Controls the temperature of the discharge lamp
4	Controls the temperature of the 10 MHz SC-cut crystal
5	Controls the temperature of the resonance cell
6	Controls the amplitude of the 10 MHz oscillator
7	Controls the peak deviation for the RF phase modulation

Example: SD2? could return the value 255 indicating that the unit has set the discharge lamp's FET drain voltage to the maximum (which it does while it is trying to start the lamp.)

The SD{port}! is a factory only command which writes the data from the corresponding SD port to the unit's EEPROM for use on subsequent restarts. **Example: SD3!?** will return the start-up value for SD3 (lamp temperature control value) which is stored in the unit's EEPROM.

Analog Test Voltages

AD{port}? port = 0,1,2,...15
Analog to digital. This command reads the voltage at the corresponding 12-bit ADC port and returns the voltage as a floating point number. Values can range from 0.000 to 4.998. The voltages correspond to various test points in the system per the following table. Note that this command can only query. **Examples: AD10?** could return the value 0.710 indicating that the case temperature sensor is at 71 °C (this sensor indicates a temperature which is about midway between the baseplate temperature and the lamp temperature.)

Command	Returned voltage
AD 0?	Spare (J204)
AD 1?	+24V(heater supply) divided by 10.
AD 2?	+24V(electronics supply) divided by 10
AD 3?	Drain voltage to lamp FET divided by 10
AD 4?	Gate voltage to lamp FET divided by 10
AD 5?	Crystal heater control voltage
AD 6?	Resonance cell heater control voltage
AD 7?	Discharge lamp heater control voltage
AD 8?	Amplified ac photosignal
AD 9?	Photocell's I/V converter voltage divided by 4
AD 10?	Case temperature (10 mV/°C)
AD 11?	Crystal thermistors
AD 12?	Cell thermistors
AD 13?	Lamp thermistors
AD 14?	Frequency calibration pot / external calibration voltage
AD 15?	Analog ground

AD{port}? $16 \leq$ port ≤ 19

A/D via CPU's E-port. This command returns a value corresponding to the voltage present at the input to the microcontroller's octal 8bit ADC (port E on the MC68HC11). Only the first four ports are in use. The voltage corresponds to various test point in the system per the following table. **Example: AD17?** could return a value of 4.81 indicating that the 360 MHz RF synthesizer has acquired lock.

Command	Returned voltage
AD 16?	Varactor voltage for 22.48 MHz VCXO (inside RF synthesizer) / 4
AD 17?	Varactor voltage for 360 MHz VCO (output of RF synthesizer) / 4
AD 18?	Gain control voltage for amplifier which drives frequency multiplier / 4
AD 19?	RF synthesizer's lock indicator voltage (nominally 4.8 V when locked)

Status Bytes

ST?

Status query. This command returns the six system status bytes which are used to indicate the health and status of the unit. The values ranges from 0 to 255. The six status bytes are detailed in the tables below. A status bit will remained set until it is read, even though the condition which caused the error has been removed. Some status bits are not errors: for example, during warmup the status bytes may indicate that the lamp is not lit, temperatures are low, and the unit is not locked.

Example: Immediately after power is applied to a unit, the command **ST?** returns 16, 3, 21, 1, 2, 129. From the status byte definitions below, we see that the following conditions exist:

16… the lamp has not yet started
3… the RF VCXO has not yet locked
21… the lamp, crystal, and cells are all below their set point temperatures
1… the frequency lock has not been established
2… fewer than 256 1pps inputs have been qualified
129.. both the lamp and unit have been restarted

ST1 : Power supplies and Discharge Lamp

ST1 bit	Condition which sets bit	Corrective Action
0	+24 for electronic < +22 Vdc	Increase supply voltage
1	+24 for electronics > +30 Vdc	Decrease supply voltage
2	+24 for heaters <+22 Vdc	Increase supply voltage
3	+24 for heaters > +30 Vdc	Decrease supply voltage
4	Lamp light level too low	Wait: check SD2 setting
5	Lamp light level too high	Check SD2 setting
6	Gate voltage too low	Wait: check SD2 setting
7	Gate voltage too high	Check SD2 setting

ST2: RF Synthesizer

ST2 bit	Condition which sets bit	Corrective Action
0	RF synthesizer PLL unlocked	Query SP? verify values
1	RF crystal varactor too low	Query SP? verify values
2	RF crystal varactor too high	Query SP? verify values
3	RF VCO control too low	Query SP? verify values
4	RF VCO control too high	Query SP? verify values
5	RF AGC control too low	Check SD0? values
6	RF AGC control too high	Check SD0? values
7	Bad PLL parameter	Query SP? verify values

ST3: Temperature Controllers

ST3 bit	Condition which sets bit	Corrective Action
0	Lamp temp below set point	Wait for warm-up
1	Lamp temp above set point	Check SD3, ambient
2	Crystal temp below set point	Wait for warm-up
3	Crystal temp above set point	Check SD4, ambient
4	Cell temp below set point	Wait for warm-up
5	Cell temp above set point	Check SD5, ambient
6	Case temperature too low	Wait for warm-up
7	Case temperature too high	Reduce ambient

ST4: Frequency Lock-Loop Control

ST4 bit	Condition which sets bit	Corrective Action
0	Frequency lock control is off	Wait for warm-up
1	Frequency lock is disabled	Enable w/LO1 command
2	10 MHz EFC is too high	SD4,SP,10MHz cal,T_{amb}
3	10 MHz EFC is too low	SP, 10 MHz cal
4	Analog cal voltage > 4.9 V	Int cal. pot, ext cal. volt
5	Analog cal voltage < 0.1	Int cal. pot, ext cal. volt
6		
7		

ST5: Frequency Lock to External 1pps

ST5 bit	Condition which sets bit	Corrective Action
0	PLL disabled	Send PL 1 to enable
1	< 256 good 1pps inputs	Provide stable 1pps inputs
2	PLL active	
3	> 256 bad 1pps inputs	Provide stable 1pps inputs
4	Excessive time interval	Provide accurate 1pps
5	PLL restarted	Provide stable 1pps inputs
6	f control saturated	Wait, check 1pps inputs
7	No 1pps input	Provide 1pps input

ST6: System Level Events

ST6 bit	Condition which sets bit
0	Lamp restart
1	Watchdog time-out and reset
2	Bad interrupt vector
3	EEPROM write failure
4	EEPROM data corruption
5	Bad command syntax
6	Bad command parameter
7	Unit has been reset

Calibration Procedures

Many applications for the PRS10 only require that the frequency of the 10 MHz output be calibrated. This may be done by adjusting a potentiometer, which is accessible through a hole in the bottom of the unit. The unit should be operating for at least 24 hours before it is calibrated. The 15 turn pot has a range of ±0.020 Hz. The frequency increases if the pot is turned clockwise, by about 0.001 Hz for 3/8's of a turn.

Note: the potentiometer position will not affect the frequency of operation if : (1) it is turned to either extreme, (2) an external control voltage is applied to pin 2 of the main connector, J100, (3) an SF (set frequency) command has been sent via the RS-232 interface, or, (4) the unit is locked to an external 1pps input. The time constant for pot adjustments depend on the setting of the frequency lock-loop gain (see GA command: the default is about 2 seconds.)

In the case that the unit cannot be calibrated because the internal pot has reached an extreme position, it will be necessary to modify a calibration values which are stored in the unit's EEPROM. To verify that the pot has been turned to a limit of its motion, measure the voltage on pin 2 (POT_W) of J100 (the main connector) with respect to the chassis. Zero volts on pin 2 indicates that the pot has been adjusted for the lowest frequency, and +5.0 Vdc indicates that the pot has been adjusted for the highest frequency.

To modify EEPROM calibration values, it will be necessary to establish RS-232 communications with the PRS10. This can be done with a three wire connection between the PC COM: port and the PRS10's main connector. A communication program (see Windows Accessories or other) will be needed as well. (See MO and SP commands.)

Circuit Descriptions

Schematic RB_F1 (sheet 1 of 7)

Components shown on this schematic are located on the vertical PCB which holds the main connector to the outside. This board has a 10MHz SC-cut ovenized oscillator which is frequency locked by the microprocessor to the hyperfine transition in rubidium via a high resolution DAC. This will overcome two important shortcomings of the oscillator circuit: frequency aging of a few parts in 10^{-10}/day , and a sensitivity of a few parts in 10^{-9} over the ambient temperature range of 0°C to 65°C.

Input Power

D101 and D102 (MBRD660CT Schottky diodes in DPAKs) protect the unit from input power supply polarity reversals on +24_CLEAN and +24_HEAT. The supplies are filtered by L104 and L105 (ferrite beads with about 3µH and Q=15 at 100kHz) and C115 and C116. These filters are designed to reduce EMI emission and susceptibility but they have a low Q resonance at about 40kHz.

Voltage Reference

U100 provides a 10.00V low noise reference for the entire unit and various biases for the crystal oscillator. The reference voltage is divided by two and buffered by U102B to provide a +5.00V reference for the internal calibration pot and for the POT+ output.

Crystal Oscillator

The crystal oscillator uses a Colpitts configuration. The 3rd overtone SC-cut crystal is specified to operate at 10.0MHz with a series load of 20pF. (Hence the crystal will operate slightly above its series resonance to contribute an inductive reactance equal in magnitude to the series capacitive reactance.) At 10MHz, the network L100, L101 and C102 has a capacitive reactance equivalent to an 87pF capacitor. At the fundamental (3.3MHz) and at the B-mode frequency (10.8MHz) this network is inductive, and so there will be no gain provided by Q100. In addition to this network, C103, C104, the varactor D100, and C106 (which connects to the ac ground at the emitter of Q101) are all in series with the crystal. C104 is selected when the unit is calibrated so that the crystal will operate at 10.0MHz with the nominal EFC voltage applied to the varactor.

The crystal frequency tunes linearly with the net series reactance, with a tuning coefficient of -1Hz/20Ω. Series capacitors tune the crystal to higher frequencies, series inductors tune the crystal to lower frequencies. Only NPO capacitors are to be used and inductors should be either air or iron powder core (no ferrites) in order to preserve the relative insensitivity to ambient temperature variations. To move the oscillator to higher frequencies, $C(pF)=808/\Delta f(Hz)$. To move the oscillator to lower frequencies, $L(\mu H)=0.29\Delta f(Hz)$.

The MMBV609 varactor provides an approximate linear tuning characteristic over ±2 ppm. This will allow the unit to correct for aging of the crystal for a nominal 27 year life, given a daily aging of 2 parts in 10^{-10}.

The crystal is operated at its temperature plateau of about 80°C. (The plateau temperature is determined at calibration for each unit.) The frequency is a maximum at the plateau and so the oscillator will typically be a few hundred Hertz low when the unit is turned on at room temperature. Near the plateau top, the frequency deviation verses temperature is about $\Delta f(Hz) = -0.061x\ \Delta T(°C)^2$. Note that if the crystal oven were to lose regulation by 12.8°C (perhaps the baseplate is too hot) that this would cause a 1ppm frequency error, which could be corrected by the Rb frequency lock loop.

Power to overcome losses (to sustain oscillation) is provided by Q100. The dominate loss is the series resistance of the crystal (about 80Ω). Q100 provides power by injecting a current at the top of L100 which is in phase with the 10MHz voltage at this node. The amount of current injected depends on the size of C103 and R103: the current injected is equal to the ac voltage across C103 divided by the resistance of R103 (assuming emitter following action of Q100). The magnitude of the oscillation will grow until the peak voltage at the base exceeds the collector voltage, causing Q100 to saturate.

The circuit is designed to allow about 1mA(rms) to circulate through the crystal. The ac current is high enough to provide low phase noise, but low enough to minimize aging. This ac current is cascoded to the inverting input of the high speed op-amp, U101, by Q101. Q101 provides a good ac ground for the crystal circuit (to maintain high in-circuit Q). With an emitter current of 4mA the emitter resistance of Q101 will be about 6Ω. Q101 also helps to isolate the crystal circuit from variations from the external 10MHz load (as does U101) so that the frequency of operation of the circuit will not be pulled by the load.

The op-amp operates as a transconductance amplifier with a transconductance gain of about 2000Ω at 10MHz. The dc output of the op-amp is midway between the supplies (at about 8.25Vdc), which is controlled by the current drawn by Q101 and the value of R111. There is a 10Vpp sine at 10MHz at the output which is ac coupled, reverse terminated, and matched to a 50Ω load by C111, R114, and T100. The primary of T100 is tuned to 10MHz, so that spurs and harmonics are attenuated. The 7:2 turns ratio transforms the 50Ω into a 612Ω load at 10MHz. The output amplitude into 50Ω is 0.50Vrms (1.414Vpp or +7dBm).

Extremely low phase noise is an important specification for this oscillator. The phase noise close to carrier (10Hz offset and below) is dominated by 1/f components, including, crystal parameters, temperature stabilization, amplitude limiting, and gain mixing. Far away from carrier (>1kHz) the noise floor is determined by ratio of broadband noise sources to the signal current at 10MHz. Examples of broadband sources include the shot noise current on base currents, the Johnson noise current from bias resistors, and the op-amp's input current and voltage noise. It is also important to maintain very low noise on the EFC and amplitude control signals. Typical phase noise is -125dBc/Hz @ 10Hz, -145dBc/Hz @ 100Hz, and -155dBc/Hz @ >1kHz.

Circuit elements and operating points were chosen to reduce noise sources. An SC-cut resonator was chosen for high Q and stable motional impedances. The transistors are operated at a few mA, trading off base bias current noise against emitter resistance. Metal film resistors are used to reduce 1/f noise. Series 100µH inductors are used to reduce the Johnson noise current of bias resistors. The op-amp was chosen for low input current noise, and it is operated with sufficient gain so that its voltage noise would not degrade the phase noise floor. Finally, the crystal is operated at its plateau temperature to reduce the frequency instability associated with temperature fluctuations.

Crystal Heater

The crystal heater has the same design as the two other heaters (resonance cell and lamp) in the system. There are two heaters in TO-220 packages: an LM340-12 (a +12Vdc voltage regulator) and a TIP107 (a pnp power Darlington). The tabs of both TO-220 heaters are at ground, so they are bolted directly to the block. All of the heater current passes through three parallel 1Ω shunt resistors to sense current. The block temperature is sensed by two series 100kΩ thermistors, which are directly beneath the TO-220 heaters in the oven block. (Two sensors are used because the division of power will depend on the heater voltage applied to the unit.) At the operating temperature of 75°C, each thermistor will have a resistance of about 15kΩ. The control circuit will allow operation up to 90°C. (For the lamp, the nominal operating temperature is 105°C, for which each thermistor will have a resistance of about 5.5kΩ. The maximum setpoint for the lamp is 122°C.) The control circuits for all of the heaters are on the top (analog) PCB. The control circuit can vary the heater current from 0 to 0.7A to maintain the set point. In the case of a control failure, the LM340-12 will turn off the current if the junction temperature reaches 125°C.

Schematic RB_F2 (Sheet 2 of 7)

The components contained on this schematic are all located on the top (analog) PCB. This board contains most of the analog circuitry for the system, including, temperature servos, photodiode amplifier and filter, analog signal multiplexers, and noise filters for the crystal's EFC and amplitude control signals.

Temperature Control Servos

There are three temperature control servos (for the crystal oven, the Rb discharge lamp, and the Rb resonance cell). The three servos are identical except for the maximum set point (122°C for the lamp, and 90°C for the others.) The circuit description will refer to the crystal temperature controller.

The controller is a proportional-integral controller. The output of the error amplifier (U200A) is used to control the current flowing in the heater circuit, with a range from 0 to 500mA (to provide heater powers from 0 to 12W). The error amplifier has a proportional gain of (R205/R204)+1=6.5 and an integration time constant of R204xC201=1 s for the signal at its

non-inverting input. The inverting input is biased near 1.00Vdc, so that the servo will try to maintain the temperature so that there is 1.00Vdc on the thermistors.

For a set point of 75°C the series thermistor pair will have a resistance of 30kΩ. To get 1.00Vdc at the non-inverting input of U200A, XTAL_SET is set to 170 bits (full-scale of 4V/255=0.01568V/bit, so 170 bits=2.66Vdc).

After settling, a LSB step in XTAL_SET (15.6mV) will become about 5.8mV at the on-inverting input, and cause an immediate change of 2x5.8mV = 11.6mV at the output of U200A, followed by a ramp of 5.8mV per second. This quickly increases the power by about 0.27W, then by 0.14W/S thereafter. The servo will settle when the thermistors heat-up, decreasing their resistance, so that the voltage at the non-inverting input returns to 1.00Vdc.

The thermistor resistance decreases by about 3%/°C. An LSB increase in XTAL_SET near the nominal 2.66Vdc will cause the current to increase by .0156/(2.66-1.00) or about 0.9%. So the servo will settle when the temperature of the block increases by 0.9%/3%/°C =0.3°C.

There is a small temperature offset between the temperature sensor and the device whose temperature we wish to control. Since the sensor is located very near the heat source, the sensor will be warmer, and the temperature offset will increase as more heat is required. To compensate for this effect, a small portion of a voltage proportional to the baseplate temperature (10mV/°C) is summed to the voltage at the inverting input of the error amplifier. This is the electronic equivalent of a double oven, as the errors due to changes in ambient temperature are greatly reduced.

U200B controls the current in the heaters in proportion to the signal from error amplifier (U200A). When the output of the error amplifier goes up, the output of U200B goes down, increasing the current in the heaters, causing the signal XTAL_SHUNT- to go down. The gain (from error amplifier to shunt voltage) is set by R207 and R208. Offsets are arranged so that the heaters will be off when the output of the error amplifier is less than +5Vdc.

Conversion to 10MHz TTL

U205 converts a 10MHz offset sinewave from the crystal oscillator into complimentary 10MHz TTL level signals. The +10MHZ signal is used as a reference for the microwave frequency synthesizer and the -10MHZ signal is used as a clock for the microprocessor. Separate signals are used to improve the isolation between the CPU and the synthesizer.

The 10MHz sine has an offset of 8.2Vdc and an amplitude of 10Vpp and is sourced via a 2.0kΩ resistor. After attenuation by R249, R250 and C210, the non-inverting input to U205 sees a signal with 0.91Vdc offset and an amplitude of 0.91Vpp, while the inverting input is biased at 0.91Vdc.

Photocell Amplifier

The output from the photocell is a sink current which is proportional to the light intensity of the discharge lamp as attenuated by the resonance cell. The light transmission through the resonance cell decreases slightly (by about 1 part in 1000) when the microwave synthesizer sweeps through the hyperfine transition frequency. The microwave frequency is modulated at 70Hz, so the light output will dip at 140Hz when centered on the hyperfine transition.

The S/N of the photocell is limited by shot noise: the shot noise current on a dc current of I amps is given by $\sqrt{(2qI)}$ (amps/$\sqrt{Hz}$) where $q=1.6x10^{-19}$. On a 50μA dc current the best we can do is 4pA/$\sqrt{Hz}$ of noise. A good design requires that the shot noise be the dominate noise term.

U206A is a low noise bipolar input op-amp whose input range includes ground. A 150kΩ metal film resistor shunted by a 1nF film capacitor is used in feedback, providing a transconductance bandwidth of 1kHz. The input current noise of the op-amp (0.4pA/$\sqrt{Hz}$) and the Johnson noise current of the feedback resistor (0.33pA/$\sqrt{Hz}$) are not important noise terms. Also, the voltage noise of the op amp (3nv/$\sqrt{Hz}$) times the noise gain (which is about 10x for a photocell whose shunt resistance is 1MΩ at 25°C, but drops to 15kΩ at the operating temperature of 80°C) is not important as the expected shot noise current times the transconductance gain is about 600nV/$\sqrt{Hz}$.

The transconductance amplifier is followed by a high gain amplifier (x288 for ac signals). This amplifier has a pass band from 16Hz to 1.6kHz. The non-inverting input to this amplifier is biased to place the output of the following bandpass filter at midscale.

A two-pole Butterworth low pass filter (300Hz bandwidth) is used to reduce noise at the A/D input, while preserving gain between 70Hz and 140Hz. The filter has a gain of 1.59 for signals in the pass band.

The input voltage noise specifications for the high gain and filter amplifiers are not particularly important as there is about 600nV/$\sqrt{Hz}$ of noise on the output of the transconductance amplifier. With an noise equivalent bandwidth of about 400Hz, we expect a total noise (from the shot noise of the photocell's dc current) of about 3.4mVrms or about 17mVpp. This is much larger than the LSB (1.25mV) of the A/D converter, so the quantization noise of the A/D will not be important.

Signal Filters for Oscillator Control

The amplitude and frequency of the crystal oscillator are controlled by signals from D/A converters. In order to preserve low phase noise, these signals must have very little voltage noise.

The EFC signal has a full scale of 17Vdc, and a resolution of 22 bits. A LSB represents a step of about 4μV which is a fractional frequency step of about $1{:}10^{-12}$. We would like for noise on the EFC to be less than one LSB. To arrange this, the DAC22 signal is filtered with a time constant of 1s and buffered by a FET input op-amp (U210B, an AD822). The FET op-amp has 1/f noise of about 2μVpp in the two decade band from 0.1Hz to 10Hz. Both the op-amp and the 10.0kΩ feed back resistor will have noise of about 30nV/√Hz at 10Hz, which is well under the target of 1.6μV/√Hz required to meet the specification of -125dBc/Hz at 10Hz offset.

The oscillator's amplitude control is filtered is a similar fashion, using U210A. Noise on this signal would be detrimental to the phase noise spectrum, but would not affect zero-crossings of the sine output.

Analog Multiplexers

There are 16 analog signals which may be multiplexed to the 12-bit A/D converter. One of these signals, PHOTO_AMP, is be digitized 32 times during each cycle of the 70Hz modulation (2240 Hz) in order to lock the crystal to the Rb hyperfine transition. The other 15 signals are monitored intermittently and in response to RS-232 requests.

A0	Amplified and filtered photocell signal
A1	Photocurrent (x150kΩ/4) (37.5mV/μA)
A2	Case temperature (10mV/°C)
A3	Crystal thermistor voltage
A4	Resonance cell thermistor voltage
A5	Lamp thermistor voltage
A6	Calibration voltage (Pot or user input)
A7	Signal Ground
B0	J204 (Spare)
B1	+24_HEAT/10
B2	+24_CLEAN/10
B3	Discharge lamp FET's drain voltage
B4	Discharge lamp FET's gate voltage
B5	Crystal heater control signal
B6	Resonance cell heater control signal
B7	Discharge lamp heater control signal

Schematic RB_F3 (Sheet 3 of 7)

All of the components shown on this schematic reside on the vertical PCB on the left side of the unit. The large hole in this PCB allows access to an SMB connector to sample the microwave field in the resonance cell.

Power on reset, low voltage protection, and a watch-dog time-out is provided by U300, a MAX705. The RESET input to the microcontroller is asserted on power-up. The reset will be asserted for about 1 second after power is applied (to allow time for the 10MHz crystal oscillator to start.). A non-maskable interrupt (XIRQ) is asserted if the SPI clock is inactive for more than 1.6 seconds, which should never occur. A maskable interrupt (IRQ) is asserted (which will also retrigger the reset cycle) when the +18V supply drops below 16.0Vdc.

Microcontroller

The system is controlled by U302, a MC68HC11E9, which is an 8-bit microcontroller with RAM, ROM, EEPROM, A/Ds, UART, serial interface, timers, and I/O control bits. The controller is clocked by the 10 MHz timebase which is to be disciplined to the atomic transition frequency.

The microcontroller communicates with external devices via a the serial peripheral interface (SPI). Data is clocked by SPI_CLK to (or from) these devices on SPI_DATA. To reduced digital crosstalk to the most sensitive devices, the SPI data and clock are gated, so that these outputs are only active when necessary.

The microcontroller is also responsible for a variety of housekeeping tasks: power on circuit checks, setting and reading temperatures, boost-starting the discharge lamp, digitally filtering the frequency-lock error signal, passing the filtered error signal to the 22 bit D/A converter, and responding to commands and queries via the RS-232 interface.

A description of I/O from the controller follows:

Name	Function
CLK	10MHz TTL clock input
RESET	TTL low to assert system reset
XIRQ	Non-maskable interrupt on watch-dog time-out (SPI dead)
IRQ	Maskable interrupt on power failure (+18 goes below +16V)
MODA	Configure for internal program memory
MODB	Configure for internal program memory
PORT A	Mixed inputs and outputs
PA0	Time tag input to measure 1PPS input to 400ns
PA1	Interpolation input to measure 1PPS input to 0.2ns
PA2	ADC_BUSY input is high during 12-bit A/D conversions
PA3	MAG_SIGN output controls sign of magnetic field
PA4	-CONV strobe low to initiate 12-bit A/D conversion
PA5	EN/-CLR control for 1PPS time-tagging
PA6	1PPS output strobe (400ns resolution)

PA7	Spare output (connected to J305)
PORT B	Eight TTL outputs
PB0	MPX0 Select bit for analog multiplexer
PB1	MPX1 Select bit for analog multiplexer
PB2	MPX2 Select bit for analog multiplexer
PB3	MPX3 Low to select MPX-A, high for MPX-B
PB4	1PPS_SEL0 Low bit for 100ns 1PPS output delay
PB5	1PPS_SEL1 High bit for 100ns 1PPS output delay
PB6	Spare (connected to J306)
PB7	LOCKED bit is set high to indicate Rb frequency lock
PORT C	Chip select outputs
PC0	-CS_PLL
PC1	-STB_DAC8
PC2	-CS_EFC_HIGH
PC3	-CS_MAGNET
PC4	Spare (connected to J308)
PC5	-CS_EFC_LOW
PC6	-CS_PHASE_MOD
PC7	EN_ADC_CLK
PORT D	SPI and RS-232
PD0	RS-232_IN
PD1	RS-232_OUT
PD2	SPI_IN
PD3	SPI_DATA
PD4	SPI_CLK
PD5	SPI_GATE
PORT E	Octal 8-bit A/D converter with +5.12V full-scale
PE0	RF_XVCO. Should be between 0.2 and 3.5Vdc
PE1	RF_VCO. Should be between 3.0 and 4.0Vdc
PE2	RF_AGC. Should be 1.0 and 3.75Vdc
PE3	PLL_LOCK. Should be >4.0Vdc
PE4	Ground
PE5	Spare analog input (J302 with 100kΩ to ground)
PE6	Spare analog input (J303 with 100kΩ to ground)
PE7	Spare analog input (J304 with 100kΩ to ground)

RS-232

The system may be controlled by commands sent via the RS-232. Two pins on the system connector (J100) are used for transmit and receive. Data is sent to the host on pin 4, received from the host on pin 7. The baud rate is fixed at 9600 baud, 8 bits, no parity, with 1 start and 2 stop bits. No DTR or CTS controls have been used, rather, the XON/XOFF protocol has been implemented. The transmit drive level is 0 and 5V, not the +/-12V normally associated with RS-232. These levels are compatible with RS-232 line receivers, but does not require their use (a TTL inverter may be used instead), hence simplifies the interface when used inside an instrument at the sacrifice of degraded noise immunity over long lines.

12 Bit A/D Conversion

A serially interfaced 12 bit A/D converter is used to measure the ac and dc components of the photocell signal. The analog input to the ADC is buffered by U309A, a FET input op-amp configured as a unit follower. The quantization noise of this converter will not degrade the S/N of the ac signal, even in the case when the ac signal occupies a relatively small portion of the converter's full scale range. The A/D converter can also measure the position of a 10 turn "user cal" pot, which has a (software defined) range of +-2E-9. The 12 bits of resolution will provide a frequency trim of 1E-12.

12-Bit Digital to Analog Converters

There are four 12-bit DACs. Two of the DACs are scaled, summed, and offset to provide a level with 22-bits of resolution to control the crystal frequency. One of the DACs is used to control the magnitude of the magnetic field in the resonance cell. The forth DAC is used to digitally synthesize the 70Hz phase modulation of the 6.834GHz microwave field.

Two of the DACs (the upper DAC of the 22-bit pair and the DAC which controls the magnetic field) are rarely changed and would be very sensitive to digital crosstalk and so are communicated with via the gated SPI interface.

Magnetic Field Control

R331, a 348Ω shunt resistor, is used to measure the current through the magnetic field coil which is in the resonance cell. U307B, an LM358 op amp, maintains a current through the field coil so that the voltage across the shunt resistor matches the output from the 12-bit DAC (U310, an LTC1452). The coil current can be programmed from 0 to 8mA, but a minimum level (3mA) is always maintained to spread out the non 0-0 Zeeman transitions. The frequency offset is quadratic in the field strength, with a fractional frequency resolution of about $1x10^{-12}$ at 3mA, and of $2.5x10^{-12}$ at 8mA.

To reduce the susceptibility of the transition frequency to external magnetic fields, the polarity of the magnetic field is chopped at 5Hz by the CPU control signal (MAG_SIGN) and U306 (a DG211 quad analog switch). The apparent transition frequency is synchronously

filtered by the CPU over the field reversal period so as to notch out any 5Hz noise from the EFC signal.

Phase Modulation

The main task for the microcontroller is to modulate the microwave carrier to sweep through the Rb hyperfine transition frequency. The microcontroller will A/D the optical signal via a 12 bit A/D converter, synchronously detect the components of the optical signal at the sweep rate and at twice the sweep rate, and adjust the frequency of the 10 MHz timebase so as to null the component at the sweep rate (which keeps the optical dip centered in the middle of the sweep).

The CPU digitally synthesizes the 70Hz sinewave which phase modulates the RF frequency synthesizer. U313, an 12-bit DAC, outputs 32 samples during each cycle of the 70Hz sinewave. The amplitude of the sinewave is controlled by the signal "PHASE_DEV", which comes from an 8-bit DAC on the frequency synthesizer PCB. The amplitude of the sinewave controls the magnitude of the frequency deviation (which is adjusted to optimize the deviation sensitivity of the resonance cell). The frequency deviation is about ±300Hz at 6.834GHz.

1PPS Output

A port bit on the microcontroller (PA7) may be used to output a 10µs pulse at a rate of 1Hz. This pulse is combined with the LOCK output signal on the main connector (pin 1 of J100). (The function of the LOCK/1PPS output may be configured via RS-232.)

This port bit is controlled by the microcontroller's timer which has a resolution of one E_CLK cycle (400ns). Hardware on the bottom circuit board provides delays in 100ns steps (under control of the port bits 1PPS_SEL0 and 1PPS_SEL1) and in steps of about 0.5ns via an analog signal from an 8-bit DAC. The combination of these three delays allows the 1PPS output pulse to be placed with an accuracy, resolution, and differential non-linearity of about 1ns.

1PPS Input Time-Tag

The rising edge of a 1PPS input signal on pin 5 of the main connector can be time-tagged with 1ns resolution. The time may reported via RS-232, or used to servo the unit to another frequency standard (such as GPS).

Hardware on the bottom board provides two signals: TIME_LATCH and INTERPOLATE. These signals latch the value of a free-running counter (clocked by the E_CLK) which is part of the microcontroller. TIME_LATCH is just the 1PPS input re-synchronized to the CPU's E_CLK, which allows the processor to time-tag the input to 400ns resolution. INTERPOLATE will go low for a time equal to about 2000 times the interval between the 1PPS input and the next E_CLK. Measuring the duration of INTERPOLATE allows the position of the 1PPS input to be measured to about 400ns/2000=0.2ns.

Schematic RB_F4. (Sheet 4 of 7)

High Resolution, Low Phase Noise, RF Synthesizer

The pressure tuned Rb hyperfine transition lies at about 6,834,685,850Hz. This will vary depending on the fill pressure and gas composition of the Rb resonance cell. In order to lock the crystal oscillator to this transition, we need to synthesize and sweep frequencies in this region.

In order to minimize the amount of magnetic field tuning needed, the frequency synthesizer should be capable of being set with high resolution (about $1{:}10^{-9}$). In order to detect the transition with good signal to noise, the synthesizer will need to have very low phase noise (on the order of -70dBc/Hz at 6.8GHz).

Since we want to stabilize a 10.000MHz crystal to an (essentially) arbitrary frequency with low phase noise, we will need a dual loop synthesizer: a fast loop to stabilize an RF VCO to a crystal (for good phase noise), and a slow loop to stabilize the crystal to the 10.000MHz reference.

Typical numbers:

A typical microwave frequency is 6,834,685,853Hz
Which is the 19th harmonic of the RF frequency: 359,720,308Hz
Which is 16 times the crystal frequency: 22,482,519Hz
In this case, dividing the RF frequency by (1386*64+39)=4053.5Hz
Which equals the reference frequency (10,000,000Hz) divided by 2467.
The dual modulus frequency synthesizer will be programmed with R=2467, N=1386, and A=39.

The microwave frequency is generated by frequency multiplication of the RF frequency in a step recovery diode (SRD). The RF frequency was chosen to give good conversion efficiency, with favorable “numerology” (so that the gaps between available frequency steps from the dual modulus synthesizer are small).

A reasonable crystal frequency is the RF frequency divided by 16 (dividers and oscillator/mixers are available in this frequency range). A third overtone crystal resonator with a nominal frequency of 22.48252MHz is used to provide a low-noise “flywheel”. We only need to tune over a range of 0.1ppm to accommodate for fill pressure variations of the resonance cell.

The varactor tuned crystal oscillator has a tuning coefficient of about 2 ppm/V. The RF VCO is phase locked to this oscillator by a mixer/loop filter combination with a high natural frequency (about 400,000r/s), a high comparison frequency (22.48MHz), and a damping factor of one. Low noise components (metal film resistors, film capacitors and an OP27 op amp) help achieve the low phase noise.

The varactor for the crystal is tuned by the dual modulus frequency synthesizer (U400, an MC145190) which compares the divided reference (10.00MHz) to the divided RF (at about 359.72MHz). Since large divisors must be used to achieve the high frequency resolution, the comparison frequency will be low (a few kHz), but the crystal oscillator provides good frequency stability in spite of the low comparison rate.

The gain of U400's phase detector may be set (coarsely) by the CPU, and it is adjusted to maintain roughly the same PLL damping factor as divisors are changed. This loop has a very low natural frequency (about 10 r/s) and a damping factor which ranges from 0.84 to 1.19.

After multiplication to 6.834GHz, the phase noise has been measured at -72dBc/Hz. This is low enough so that the S/N of the dip signal is not adversely affected by the microwave phase noise.

RF Output Amplifier

The 359.720MHz RF must be amplified to drive the SRD. It is important to maintain a constant RF level, optimized to provide a large frequency deviation sensitivity and immunity to RF level variations.

The variable gain output amplifier is designed to provide a conjugate match of Q400 (an MFR5812 medium power RF transistor) to the 50Ω source (U404, the VCO) and to the 50Ω load (the SRD, which has its own matching network).

The gain of Q400 is adjusted by changing its dc collector current. U406A compares the DAC signal (RF_LEVEL) to the rectified RF current in the SRD (which is the dc current sourced by R444). If the detected RF is low, the output of U406A will ramp up, increasing the output of U406B, which increases the base current to Q400, increasing the available power from Q400. The output of U406A linearly controls the collector current of Q400 from 0 to about 35mA. U406A's output settles when the detected RF signal on R444 is exactly 1/10th of the RF_LEVEL DAC signal.

Step Recovery Diode Matching

The output of the RF amplifier is connected to the SRD via an SMB connector. The SRD can be modeled at RF frequencies and at our drive level as a resistor (20-40Ω, depending on drive level) with a shunt capacitor (about 1pF) and a series inductor (a few nH). Matching (for best return loss) is achieved by adding a shunt capacitor (5pF) across the SMB and with a series inductor (10nH) to the SRD.

The SRD is inside the mu-metal can which encloses the resonance cell and photodetector. The can is not resonant at the microwave frequency (as is common practice), and so there is no need to tune the length of the cavity or worry about the affect of coming off resonance. Sufficient field strength at 6.834GHz is available without resonant enhancement due to the high RF drive frequency and efficient coupling into the SRD.

The SRD loop is oriented inside the can in such a way as to minimize the drive level required for a good hyperfine optical signal.

Analog Control

Various analog voltages are provided by an octal 8-bit DAC to control temperatures, intensities, and for system tests. U407, a TLC5628, is connected to the microcontroller via the gated serial interface. Each of the eight analog outputs may be set from 0 to 4.00V with 10mV resolution. (Except for the PHASE_DEV output, which has a full scale of 2.00V and a step size of 5mV.) The outputs are dedicated as follows:

OUTPUT	NAME	DESCRIPTION
A	RF_LEVEL	Controls the RF power level to the SRD
B	1PPS_DELAY	Analog control of 1PPS output delay (0.5ns/bit)
C	LAMP_DRAIN	Drain voltage (x6) to lamp FET
D	LAMP_TSET	Controls the lamp temperature (Tmax=122°C)
E	XTAL_TSET	Controls the crystal temperature (Tmax=90°C)
F	CELL_TSET	Controls the cell temperature (Tmax=90°C)
G	OSC_AMPL	Controls the 10.00MHz output amplitude
H	PHASE_DEV	Controls the frequency deviation of RF

Schematic RB_F5 (Sheet 5 of 7)

Power Supply, Lamp Control and 1PPS Timing PCB

Components shown on this schematic are located on the bottom PCB. Three TO-220 power regulators are mounted to the back wall of the device.

Linear Power Supplies

All of the power supplies operate from the +24_CLEAN input (pin 9 of the main connector). U503, an LM317 adjustable voltage regulator, is used to supply +18Vdc to the system. The +18V is used on the analog PBC, on the frequency synthesizer, for the crystal oscillator, and for the analog switches and ADC buffer on the CPU PCB.

U504, an LM340-5 three terminal regulator is used to provide +5.0Vdc. This supply is used for all logic circuits and for analog circuits which interface to analog devices which must not be driven above their logic supplies.

Lamp Regulator

A discharge is ignited and maintained by a MOSFET powered oscillator operating at about 150MHz inside the lamp enclosure. It is very important that the voltage provided to the lamp circuit be well regulated, as the lamp intensity is nearly proportional to this voltage. Since the synchronously detected light signal at 70Hz is used to lock to the hyperfine transition, noise at 70Hz will add noise to the frequency lock-loop. Also, noise at other frequencies may be heterodyned by the 2ω signal (140Hz), which is really a modulation of the attenuation of light through the resonance cell. For example, if the power supply has noise at 210Hz, the lamp will have an intensity fluctuation at 210Hz, which when mixed by the 140Hz attenuation modulation will create a component at 70Hz, which will interfere with the frequency lock loop.

Long term stability (thermal and aging) of the lamp voltage regulator is also important. The voltage provided to the lamp oscillator affects the operating conditions of the lamp (temperature, Rb vapor pressure, and discharge intensity) which will affect the apparent hyperfine transition frequency.

The drain voltage and current are controlled by the lamp regulator. The gate voltage to the MOSFET is controlled so that the drain current is about 60mA + (10mA/V)*V_{drain}. The gate voltage is supplied by U502B which measures the drain current through the shunt resistors R504, R505, R552 and R553. The offset and slope of the drain current vs. drain voltage is set by R510 and R511.

The drain voltage is controlled by an 8bit DAC whose output is multiplied by 6 and buffered by U502 and Q500. An adjustable regulator, U501, is bootstrapped at 1.75Vdc above the drain voltage. This regulator will provide the drain current for drain voltages above 6.25Vdc. When the drain voltage is set below 6.25Vdc, the drain current is sourced from a +8V regulator, which is part of the lamp heater circuit. (This is done to reduce the power required by the unit by redirecting the heat of the regulator to the lamp block which needs to operate at a high temperature.)

To start the discharge, the drain voltage to the MOSFET is set to about 20Vdc, which is regulated from the +24_HEAT supply. The drain voltage is reduced to about 5V after the lamp starts.

1PPS Input Time-Tag

The rising edge of a 1PPS input signal on pin 5 of the main connector can be time-tagged with 1ns resolution. The time may reported via RS-232, or used to servo the unit to another frequency standard (such as GPS).

Hardware on this board provides two signals: TIME_LATCH and INTERPOLATE. These signals latch the value of a free-running counter (clocked by the E_CLK) which is part of the microcontroller. TIME_LATCH is just the 1PPS input re-synchronized to the CPU's

E_CLK, which allows the processor to time-tag the input to 400ns resolution. INTERPOLATE will go low for a time equal to about 2000 times the interval between the 1PPS input and the next E_CLK. Measuring the duration of INTERPOLATE allows the position of the 1PPS input to be measured to about 400ns/2000=0.2ns.

The E_CLK is synchronized to the 10MHz clock, and four phases are generated by U500, an octal latch. E_0 is used to synchronize EN/-CLR (U506A), and E_90 is used to arm the time-tagging circuit (U507A). A gate pulse (the output of U507B) will start with the first 1PPS input after U507A is set, and end synchronously with the first E_180 rising edge after the first E_90 rising edge after the 1PPS input. This will generate a gate pulse of 100ns to 500ns duration that is a measure of the position of the 1PPS input relative to the E_CLK.

The width of the gate pulse is multiplied by a factor of about 2000 by the pulse stretcher circuit. Initially, C509 is charged to 11.4Vdc. C509 is rapidly discharged by Q502's collector current (about 10.8mA) during the gate pulse, driving the output of the comparator (U509) low. C509 is then recharged by Q501, a 5.4µA constant current source. When C509 reaches 11.0V, the output of the comparator goes high. The ratio of the collector currents of Q501 and Q502 sets the stretch multiplier.

The circuit is temperature compensated against variations in the transistors' base-emitter voltages as both the charge and discharge currents are equally affected by their junction temperature, leaving the ratio unchanged.

1PPS Output Pulse Delay

A port bit on the microcontroller (PA7) may be used to output a 10µs pulse at a rate of 1Hz. This port bit is controlled by the microcontroller's timer which has a resolution of one E_CLK cycle (400ns). Hardware on this circuit board provides delays in 100ns steps (under control of the port bits 1PPS_SEL0 and 1PPS_SEL1) and in steps of about 0.5ns via an analog signal from an 8-bit DAC. The combination of these three delays allows the 1PPS output pulse to be placed with an accuracy, resolution, and differential non-linearity of about 1ns.

The 1PPS port bit from the CPU is synchronized to E_0 by U506B, then synchronized and delayed by U500. The multiplexer, U510, selects one of the four phases of the 1PPS output, delayed in steps of 100ns by the 10MHz clock.

The selected 1PPS pulse may be delayed by an analog control signal. C513 is charged to a level of $10+V_{dac}/2$ by Q503's collector current, which turns on D503, connecting C513 to the output of U512B. The selected 1PPS output turns Q503's current down, and turns Q504's current up, discharging C513. As C513 passes through 9.0Vdc, the comparator output (U514) is forced low. C513 continues to discharge down to $8- V_{dac}/2$, where it stays until the 1PPS pulse goes low. When the 1PPS pulse goes low, the process is reversed, and Q504's current is reduced while Q503's current is increased, charging C513 back towards $10+V_{dac}/2$. This

time, as C513 passes through 9.0V, the comparator's output is set high. In this way, both the leading and trailing edges off the 1PPS output are delayed the same amount.

Baseplate Temperature Sensor

U505, an LM45 centigrade temperature sensor, has an output of 10mV/°C. This sensor is in thermal contact with one of the baseplate standoffs that hold the thermal shield which encloses the lamp. The sensor's output may be read by the CPU via the 12-bit DAC so that the baseplate temperature may be read with 0.125°C resolution.

The output of the temperature sensor is also used to tweak the setpoints of the temperature control servos, which will reduce the affect of ambient temperature changes on the temperatures of the lamp, resonance cell, and crystal ovens.

Schematic RB_F6 (Sheet 6 of 7)

Resonance Cell and Lamp Heaters

The heater and control circuits for the lamp and resonance cell are identical to the circuit described for the crystal oscillator. (See Sheet 1 of 1.) The resonance cell heaters (U600 and Q600) are located on the back of the resonance cell. The lamp heaters (U800 and Q800) are located on the bottom of the lamp block. The other passive components are located on the small vertical PBCs attached to the back of the resonance cell and lamp blocks. The control circuits of the heaters are located on the top PCB.

Resonance Cell

Components shown inside the resonance cell include: L700, a 50 turn magnetic field coil, D700, the SRD with its input matching network mounted on an SMB connector, and D701, the photodiode. Another SMB connector, J701, is used to pick-up some of the microwave field to allow diagnostic tests with an RF spectrum analyzer.

Discharge Lamp

A plasma discharge is maintained inside a small bulb (filled with a few Torr of an inert gas and some Rb metal) by an RF oscillator. The oscillator operates at about 150MHz, with a peak-to-peak voltage of about 10 times the dc voltage applied to the FET's drain.

Q900, an MRF134 medium power n-channel FET, is used as the active element in the oscillator circuit. This part is characterized for operation at +28Vdc and 150MHz, and is rated for a dissipation of 9.5W (derated for our 105°C operation). Our most severe operation is during lamp ignition, with an total input power of about 3.2W. The total input power during normal operation is 0.5W. (The power dissipated in the MRF134 is probably about 1/2 the total input power.)

The oscillator current circulates through the series LC network consisting of C903-906 and L903. The coil, L903, is in contact with the bulb. The high voltage end of the coil connects to C905. When oscillating, the drain of the FET swings between ground and twice the dc drain voltage. C903 is in parallel with the FET's drain-source capacitance (about 10pF), for a total capacitance of 78pF (or a reactance of about –j13.6Ω at 150MHz). With a drain voltage of 20Vdc, the drain will have about 40V peak-to-peak, so there will be a circulating current of 2.9A, peak-to-peak. The series capacitance of C904/C905 is 9pF (a reactance of about -j118Ω), so they will have about 340Vpp across the pair (due to the circulating current), which is in phase with the 40Vpp drain voltage, for a total of 380Vpp at the top of the coil.

It is very important that C903-906 be very low loss and high stability capacitors. Porcelain capacitors are used in this circuit: they have Qs of about 500, for ESRs of about 0.03Ω (for the 56pF part at 150MHz). Low loss is important to reduce self-heating (which can destroy other types of capacitors), and high stability is important to maintain a constant discharge intensity.

The operation of the oscillator depends somewhat on the conditions of the discharge. Over certain temperature ranges (which are carefully avoided) the losses caused by the discharge can quench the oscillation, which stops the discharge, which allows the oscillation to start again. This cycle can occur at several kHz, which makes frequency locking impossible.

Schematic RB_F7 (Sheet 7 of 7)

Connector Interface Board (Not part of standard product)

This board is not part of the standard product and is available from the factory at and additional charge. It is intended to facilitate customer evaluation of the product by adapting the standard product's interface connector to connector types which are more readily available in the laboratory (such as BNCs and DB9 for RS-232).

This board connects to the outside of the unit. Three BNCs are used to source 10MHz and the 1PPS outputs, and to receive the 1PPS input. A DB9(female) allows direct connection to a computer (usually via COM2:). A 2.1mm power connector allows the unit to be connected to a standard +24V/2.5A power supply (center conductor must be positive).

The 10MHz output should be terminated into a 50Ω load. The output will be about 0.5Vrms (about 1.41Vpp).

The RS-232 interface uses CMOS logic levels (0V and +5V) which will work with standard RS-232 line drivers and receivers. The ±12V of the standard RS-232 line driver will not harm the logic input, and the 0/+5V RS-232 output from the rubidium standard will work with virtually all computers, provided the cable is less than 25 feet long. The RS-232 control lines, CD, DSR and CTS are all pulled high via 10kΩ resistors. An XON/XOFF protocol is used to pause communications as needed.

The LOCK/1PPS function may be configured via RS-232. The factory default is a low level to indicate lock, with a 10μs pulse to +5V at 1PPS, with the leading edge being defined as the 1PPS timing reference. This BNC output is a CMOS logic output via a 1kΩ resistor. LEDs are used to indicate +24 power (electronics and heaters), lock status, and RS-232 data received and RS-232 data transmitted.

Appendix A: Frequency Synthesizer Table

This table provides a list of frequency synthesizer parameters and the frequency offset relative to the settings for a nominal cell. Also listed is the frequency step between adjacent settings.

This information is needed to calibrate units which have aged by more than $\pm 2x10^{-9}$, or in the case that an application may require operating the unit at a frequency up to 0.6Hz away from 10MHz.

Number	R	N	A	f-fo(Hz)	df(hz)
1	6900	3878	15	0.000000	
2	6757	3797	55	-0.005963	0.005963
3	6614	3717	31	-0.012183	0.006220
4	6471	3637	7	-0.018678	0.006495
5	6328	3556	47	-0.025467	0.006789
6	6185	3476	23	-0.032570	0.007103
7	6042	3395	63	-0.040009	0.007439
8	5899	3315	39	-0.047809	0.007800
9	5756	3235	15	-0.055996	0.008187
10	5613	3154	55	-0.064600	0.008604
11	5470	3074	31	-0.073654	0.009054
12	5327	2994	7	-0.083195	0.009540
13	5184	2913	47	-0.093261	0.010067
14	5041	2833	23	-0.103899	0.010638
15	4898	2752	63	-0.115158	0.011259
16	4755	2672	39	-0.127094	0.011936
17	4612	2592	15	-0.139771	0.012676
18	4469	2511	55	-0.153258	0.013488
19	4326	2431	31	-0.167638	0.014379
20	4183	2351	7	-0.183000	0.015362
21	4040	2270	47	-0.199450	0.016450
22	3897	2190	23	-0.217108	0.017657
23	3754	2109	63	-0.236110	0.019002
24	3611	2029	39	-0.256618	0.020508
25	7079	3978	54	-0.267493	0.010875
26	3468	1949	15	-0.278816	0.011324
27	6793	3818	6	-0.290617	0.011800
28	3325	1868	55	-0.302924	0.012308
29	6507	3657	22	-0.315773	0.012849
30	3182	1788	31	-0.329199	0.013426
31	6221	3496	38	-0.343243	0.014043
32	3039	1708	7	-0.357947	0.014704
33	5935	3335	54	-0.373360	0.015413
34	2896	1627	47	-0.389534	0.016174
35	5649	3175	6	-0.406527	0.016993
36	2753	1547	23	-0.424402	0.017875

Number	R	N	A	f-fo(Hz)	df(hz)
37	5363	3014	22	-0.443231	0.018829
38	2610	1466	63	-0.463091	0.019860
39	5077	2853	38	-0.484071	0.020979
40	2467	1386	39	-0.506266	0.022195
41	7258	4079	29	-0.521791	0.015526
42	4791	2692	54	-0.529786	0.007995
43	7115	3999	5	-0.537941	0.008155
44	2324	1306	15	-0.554753	0.016812
45	6829	3838	21	-0.572269	0.017516
46	4505	2532	6	-0.581306	0.009036
47	6686	3757	61	-0.590535	0.009229
48	2181	1225	55	-0.609599	0.019064
49	6400	3597	13	-0.629515	0.019916
50	4219	2371	22	-0.639810	0.010295
51	6257	3516	53	-0.650341	0.010531
52	2038	1145	31	-0.672141	0.021800
53	5971	3356	5	-0.694986	0.022845
54	3933	2210	38	-0.706824	0.011838
55	5828	3275	45	-0.718952	0.012128
56	1895	1065	7	-0.744123	0.025171
57	5542	3114	61	-0.770593	0.026470
58	3647	2049	54	-0.784348	0.013754
59	5399	3034	37	-0.798466	0.014118
60	7151	4019	20	-0.805666	0.007200
61	1752	984	47	-0.827855	0.022189
62	6865	3858	36	-0.850968	0.023113
63	5113	2873	53	-0.858888	0.007920
64	3361	1889	6	-0.875065	0.016177
65	4970	2793	29	-0.891707	0.016642
66	6579	3697	52	-0.900209	0.008502
67	1609	904	23	-0.926471	0.026261
68	6293	3537	4	-0.953926	0.027455
69	4684	2632	45	-0.963357	0.009431
70	3075	1728	22	-0.982657	0.019301
71	4541	2552	21	-1.002566	0.019908
72	6007	3376	20	-1.012757	0.010191
73	1466	823	63	-1.044325	0.031568

Number	R	N	A	f-fo(Hz)	df(hz)
74	7187	4039	35	-1.070709	0.026385
75	5721	3215	36	-1.077471	0.006761
76	4255	2391	37	-1.088890	0.011420
77	7044	3959	11	-1.098166	0.009275
78	2789	1567	38	-1.112316	0.014150
79	6901	3878	51	-1.126759	0.014444
80	4112	2311	13	-1.136556	0.009796
81	5435	3054	52	-1.148995	0.012439
82	6758	3798	27	-1.156563	0.007569
83	1323	743	39	-1.187656	0.031093
84	6472	3637	43	-1.220123	0.032467
85	5149	2894	4	-1.228465	0.008342
86	3826	2150	29	-1.242576	0.014111
87	6329	3557	19	-1.254056	0.011480
88	2503	1406	54	-1.271605	0.017548
89	6186	3476	59	-1.289559	0.017954
90	3683	2070	5	-1.301761	0.012202
91	4863	2733	20	-1.317282	0.015521
92	6043	3396	35	-1.326742	0.009460
93	7223	4059	50	-1.333111	0.006369
94	1180	663	15	-1.365727	0.032616
95	6937	3899	2	-1.399688	0.033961
96	5757	3235	51	-1.406649	0.006961
97	4577	2572	36	-1.417199	0.010550
98	3397	1909	21	-1.435079	0.017880
99	5614	3155	27	-1.449656	0.014577
100	2217	1246	6	-1.471991	0.022336

Appendix B: Precision Frequency Measurement

One goal for the calibration of the PRS10 is to set the frequency to within 1 part in 10^{11} of 10MHz (which is 10MHz ± 0.0001Hz, or 10MHz ±100μHz). Two things are required to make this measurement: (1) a very good 10MHz frequency reference, and, (2) a very good time-interval counter.

The frequency reference should be stable and accurate to a few parts in 10^{12}. Another PRS10 locked to the 1pps from a GPS receiver, or a cesium beam standard (such as HP 5071A), are two possibilities.

The time-interval counter needs to measure time intervals with a resolution of better than 50ps, and should be able to do fast averaging of the time-interval measurements. Suitable instruments include the SR620 or an HP5370B.

The time-interval counter may be used to directly measure the frequency of the device under test (DUT). In this case, the frequency reference is used as the timebase for the time-interval counter. Unfortunately, the time-interval counter will require about 100 seconds to measure the frequency to a resolution of 1 part in 10^{12} when used in the frequency measurement mode.

A faster way to make the comparison between the reference frequency and the DUT is to use the time interval measurement mode of the counters. In this case, the time intervals between the 10MHz zero crossings of the reference frequency and the DUT are measured and averaged. If this time interval changes by less than 10ps per second, then the DUT is within 1 part in 10^{11} of the frequency reference.

This technique is very similar to the technique of offsetting the reference frequency from the DUT, mixing the two sources, amplifying and filtering and measuring the frequency of the beatnote. (Often referred to as a heterodyne measurement.) However, the time interval measurement technique does not require mixers or amplifiers or offsetting the reference from the DUT.

The resolution of the time-interval technique is remarkable. Each time-interval measurement has an rms jitter of about 25ps (in the case of the SR620). As the jitter is randomly distributed, the jitter of the mean is reduced by the square root of the number of samples. For a 1000 sample measurement, (which takes less than one second to complete) the rms jitter of the mean will be less than 1ps, and the difference between two time interval measurements will have a jitter of less than 2ps. This provides a relative frequency measurement to 2 parts in 10^{12} in 2 seconds.

Set-up for an SR620

Described here is the set-up for an SR620 Time Interval Counter to make precision frequency measurements. For a detailed description for the operation of the SR620, refer to the instrument's operation and service manual.

Four input connections:

The 10MHz reference frequency is connected to both the rear panel 10MHz input and to the "A" (START) input. (Place the tee on the rear panel input.)
Connect the 10MHz from the DUT to the "B" (STOP) input.
Connect the 1kHz TTL square wave from "REF" output to gate "EXT" input BNC.

Four input setups:

From the front panel "CONFIG" menu, use "SET" to choose the "cAL" menu, then use "SELECT" to select the "cLoc SourcE". Use the arrow keys to set the clock source to "rEAr". This will allow the SR620 to use the 10MHz reference frequency which has been applied to the rear panel 10MHz input as the timebase for all measurements.

Set the "EXT" gate input "LOGIC" to POS, "TERM" to 50Ω, and "LEVEL" to +1.0V. The "TRIG" LED will go on when the "GATE/ARM" is setup properly.

Both "A" (START) and "B" (STOP) are AC coupled and terminated into 50Ω. The "SLOPE" is set to "+", and the "LEVEL" is turned full counter-clockwise to "AUTO" and the "UHF" LED should be off. The "TRIG" LEDs will be on when the 10MHz sources are present.

"Coarse" Frequency Measurements

You should verify that the DUT is very close (within 0.1Hz) to 10MHz. To measure the frequency, set "MODE" to "FREQ", set "SOURCE" to "B", set the "GATE/ARM" to 1s, and set the "SAMPLE SIZE" to 1. Hold the "START" button down for a few seconds to start continuous measurements. Set the display to "MEAN" to display the frequency of the 10MHz output from the DUT.

"Fine" Frequency Measurements

If the 10MHz from the DUT is within 0.1Hz of 10MHz, you may use the "fine" frequency measurement technique to make measurements to a few parts in 10^{12} in a one second interval. As explained above, the frequency offset between the reference and the DUT is inferred by time-interval measurements between their zero-crossings.

To carry out these measurements: Set the "MODE" to "TIME", select the "SOURCE" (of START) to "A", set the "GATE/ARM" mode to "+TIME" and "EXT", and set the

"SAMPLE SIZE" to 1000. With the external gate triggered by the SR620's 1kHz reference output, the unit will display a new "MEAN" every second. If the DUT is adjusted so that the mean of the time interval measurements changes by less than 10ps per second, then the DUT is within 1 part of 10^{11} of the reference frequency.

Parts list for Revision H

Part reference numbers may be used to help locate the part per the following table:

Reference Designator	Location
100 to 149	10MHz oven oscillator (front vertical) PCB
150 to 199	Crystal heater PCB (front vertical)
200 to 299	Analog servos and amplifiers (top) PCB
300 to 399	Microcontroller (left-side, vertical) PCB
400 to 499	Frequency synthesizer (right side, vert) PCB
500 to 599	P/S and 1PPS circuits (bottom) PCB
600 to 699	Cell heater PCB (rear vertical)
700 to 799	Inside the resonance cell
800 to 899	Lamp heater PCB (center vertical)
900 to 999	Inside lamp enclosure

REF.	SRS PART	VALUE	DESCRIPTION
C 100	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 101	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 102	5-00370-552	39P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 103	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 106	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 107	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 108	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 109	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
C 110	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 111	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 112	5-00361-552	6.8P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 113	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 114	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 115	5-00472-569	4.7U/T35	Cap, Tantalum, SMT (all case sizes)
C 116	5-00472-569	4.7U/T35	Cap, Tantalum, SMT (all case sizes)
C 151	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 152	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 200	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 201	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 202	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 203	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 204	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 205	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 206	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 207	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 208	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 210	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO

REF.	SRS PART	VALUE	DESCRIPTION
C 212	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 216	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 217	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 218	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 219	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 220	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 221	5-00454-572	.01U	SMT Film Capacitors, 50V, 5%, All Sizes
C 222	5-00454-572	.01U	SMT Film Capacitors, 50V, 5%, All Sizes
C 223	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 224	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 226	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 227	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 228	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 229	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 230	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 301	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 302	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 304	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 306	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 308	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 309	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 310	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 311	5-00472-569	4.7U/T35	Cap, Tantalum, SMT (all case sizes)
C 400	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 401	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 402	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 403	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 404	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 405	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 406	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 407	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 408	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 409	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 410	5-00462-572	.047U	SMT Film Capacitors, 50V, 5%, All Sizes
C 411	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 413	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 414	5-00373-552	68P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 415	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 416	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 417	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 418	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 419	5-00456-572	.015U	SMT Film Capacitors, 50V, 5%, All Sizes
C 420	5-00456-572	.015U	SMT Film Capacitors, 50V, 5%, All Sizes
C 421	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 422	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 423	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 424	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 425	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 426	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 427	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO

REF.	SRS PART	VALUE	DESCRIPTION
C 428	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 429	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 430	5-00359-552	4.7P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 431	5-00356-552	2.7P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 432	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 433	5-00364-552	12P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 434	5-00366-552	18P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 436	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 437	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 438	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 439	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 440	5-00466-572	.1U	SMT Film Capacitors, 50V, 5%, All Sizes
C 500	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 502	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 504	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 506	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 507	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 508	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 509	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 510	5-00356-552	2.7P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 511	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 512	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 513	5-00376-552	120P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 514	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 515	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 516	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 517	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 518	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 519	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 520	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 521	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 600	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 601	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 602	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 700	5-00480-574	5.6P 500V	SMT, High Voltage Porcelain Cap.
C 800	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 801	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 802	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 803	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 804	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 805	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 900	5-00100-517	2.2U	Capacitor, Tantalum, 35V, 20%, Rad
C 903	5-00487-574	68P 500V	SMT, High Voltage Porcelain Cap.
C 904	5-00479-574	18P 500V	SMT, High Voltage Porcelain Cap.
C 905	5-00479-574	18P 500V	SMT, High Voltage Porcelain Cap.
C 906	5-00487-574	68P 500V	SMT, High Voltage Porcelain Cap.
D 100	3-00803-360	MMBV609	Integrated Circuit (Surface Mount Pkg)
D 101	3-00648-360	MBRD660CT	Integrated Circuit (Surface Mount Pkg)
D 102	3-00648-360	MBRD660CT	Integrated Circuit (Surface Mount Pkg)
D 202	3-00538-360	MMBD352L	Integrated Circuit (Surface Mount Pkg)

REF.	SRS PART	VALUE	DESCRIPTION
D 203	3-00854-313	ZMM5230B	Diode, SMT
D 204	3-00854-313	ZMM5230B	Diode, SMT
D 205	3-00854-313	ZMM5230B	Diode, SMT
D 400	3-00803-360	MMBV609	Integrated Circuit (Surface Mount Pkg)
D 401	3-00803-360	MMBV609	Integrated Circuit (Surface Mount Pkg)
D 500	3-00648-360	MBRD660CT	Integrated Circuit (Surface Mount Pkg)
D 501	3-00806-360	BAV170LT1	Integrated Circuit (Surface Mount Pkg)
D 502	3-00649-360	BAW56LT1	Integrated Circuit (Surface Mount Pkg)
D 503	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 504	3-00806-360	BAV170LT1	Integrated Circuit (Surface Mount Pkg)
D 700	3-00235-308	47402-15	Diode, Step Recovery
J 100	1-00319-166	10 PIN MALE	Connector, D-Sub, Male
J 100X	1-00320-100	COAX INSERT	Connector, Misc.
J 400	1-00224-141	STRAIGHT PLUG	SMB Connector
J 700	1-00222-141	REAR MT JACK	SMB Connector
J 701	1-00222-141	REAR MT JACK	SMB Connector
J 800	6-00017-630	FB43-301	Ferrite Beads
J 801	6-00017-630	FB43-301	Ferrite Beads
J 802	6-00017-630	FB43-301	Ferrite Beads
JP500	1-00323-130	64 PIN STRIP	Connector, Male
JP501	1-00324-130	64 HDR PIN R/A	Connector, Male
L 100	6-00171-606	4.7UH-5PH	Inductor, Variable
L 101	6-00171-606	4.7UH-5PH	Inductor, Variable
L 102	6-00264-609	100UH - SMT	Inductor, Fixed, SMT
L 103	6-00264-609	100UH - SMT	Inductor, Fixed, SMT
L 104	6-00174-630	6611 TYPE 43	Ferrite Beads
L 105	6-00174-630	6611 TYPE 43	Ferrite Beads
L 200	6-00236-631	FR47	Ferrite bead, SMT
L 300	6-00236-631	FR47	Ferrite bead, SMT
L 301	6-00236-631	FR47	Ferrite bead, SMT
L 302	6-00236-631	FR47	Ferrite bead, SMT
L 400	6-00530-609	.027UH - SMT	Inductor, Fixed, SMT
L 401	6-00513-609	.012UH - SMT	Inductor, Fixed, SMT
L 402	6-00266-609	.18UH - SMT	Inductor, Fixed, SMT
L 403	6-00281-609	2.2U - SMT	Inductor, Fixed, SMT
L 902	6-00011-603	1.0U	Inductor, Axial
LX104	0-00772-000	1.5" WIRE	Hardware, Misc.
LX105	0-00772-000	1.5" WIRE	Hardware, Misc.
P 100	4-01576-459	50K 9MM SIDE	Pot, Multi-Turn Cermet, Various sizes
PC1	7-00767-701	RB MULTIPLES	Printed Circuit Board
Q 100	3-00808-360	MMBR5179	Integrated Circuit (Surface Mount Pkg)
Q 101	3-00555-360	MMBR941L	Integrated Circuit (Surface Mount Pkg)
Q 150	3-00325-329	TIP107	Voltage Reg., TO-220 (TAB) Package
Q 400	3-00895-360	NE461M02	Integrated Circuit (Surface Mount Pkg)
Q 500	3-00807-360	MJD47	Integrated Circuit (Surface Mount Pkg)
Q 501	3-00540-360	MMBT5087	Integrated Circuit (Surface Mount Pkg)
Q 502	3-00808-360	MMBR5179	Integrated Circuit (Surface Mount Pkg)
Q 503	3-00809-360	MMBTH81LT1	Integrated Circuit (Surface Mount Pkg)
Q 504	3-00810-360	MMBTH10LT1	Integrated Circuit (Surface Mount Pkg)
Q 600	3-00325-329	TIP107	Voltage Reg., TO-220 (TAB) Package

REF.	SRS PART	VALUE	DESCRIPTION
Q 800	3-00325-329	TIP107	Voltage Reg., TO-220 (TAB) Package
Q 900	3-00665-360	MRF134	Integrated Circuit (Surface Mount Pkg)
R 100	4-01242-462	20.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 101	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 102	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 103	4-00954-462	20	Thin Film, 1%, 50 ppm, MELF Resistor
R 104	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 105	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 106	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 107	4-01088-462	499	Thin Film, 1%, 50 ppm, MELF Resistor
R 108	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 109	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 110	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 111	4-01067-462	301	Thin Film, 1%, 50 ppm, MELF Resistor
R 112	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 113	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 114	4-01096-462	604	Thin Film, 1%, 50 ppm, MELF Resistor
R 115	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 116	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 117	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 118	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 119	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 120	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 121	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 123	4-00925-462	10	Thin Film, 1%, 50 ppm, MELF Resistor
R 150	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 151	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 153	4-00899-431	P1H104-T-NTC	Thermistor, various
R 154	4-00899-431	P1H104-T-NTC	Thermistor, various
R 200	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 201	4-01305-462	90.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 202	4-01295-462	71.5K	Thin Film, 1%, 50 ppm, MELF Resistor
R 203	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 204	4-01557-461	1.8M	Thick Film, 5%, 200 ppm, Chip Resistor
R 205	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 206	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 207	4-01376-462	499K	Thin Film, 1%, 50 ppm, MELF Resistor
R 208	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 209	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 210	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 211	4-01278-462	47.5K	Thin Film, 1%, 50 ppm, MELF Resistor
R 213	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 214	4-01305-462	90.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 215	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 216	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 217	4-01557-461	1.8M	Thick Film, 5%, 200 ppm, Chip Resistor
R 218	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 219	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 220	4-01376-462	499K	Thin Film, 1%, 50 ppm, MELF Resistor
R 221	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor

REF.	SRS PART	VALUE	DESCRIPTION
R 222	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 223	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 224	4-01278-462	47.5K	Thin Film, 1%, 50 ppm, MELF Resistor
R 226	4-01238-462	18.2K	Thin Film, 1%, 50 ppm, MELF Resistor
R 227	4-01305-462	90.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 228	4-01363-462	365K	Thin Film, 1%, 50 ppm, MELF Resistor
R 229	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 230	4-01557-461	1.8M	Thick Film, 5%, 200 ppm, Chip Resistor
R 231	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 232	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 233	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 234	4-01376-462	499K	Thin Film, 1%, 50 ppm, MELF Resistor
R 235	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 236	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 237	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 238	4-01278-462	47.5K	Thin Film, 1%, 50 ppm, MELF Resistor
R 240	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 241	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 248	4-01439-461	22	Thick Film, 5%, 200 ppm, Chip Resistor
R 249	4-01059-462	249	Thin Film, 1%, 50 ppm, MELF Resistor
R 250	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 252	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 256	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 261	4-01355-462	301K	Thin Film, 1%, 50 ppm, MELF Resistor
R 262	4-01355-462	301K	Thin Film, 1%, 50 ppm, MELF Resistor
R 263	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 264	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 265	4-01098-462	634	Thin Film, 1%, 50 ppm, MELF Resistor
R 266	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 267	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 268	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 269	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 270	4-01347-462	249K	Thin Film, 1%, 50 ppm, MELF Resistor
R 271	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 272	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 273	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 274	4-01191-462	5.90K	Thin Film, 1%, 50 ppm, MELF Resistor
R 275	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 276	4-01305-462	90.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 277	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 278	4-01305-462	90.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 279	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 280	4-01305-462	90.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 281	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 282	4-01305-462	90.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 283	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 284	4-01294-462	69.8K	Thin Film, 1%, 50 ppm, MELF Resistor
R 285	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 286	4-01294-462	69.8K	Thin Film, 1%, 50 ppm, MELF Resistor
R 287	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor

REF.	SRS PART	VALUE	DESCRIPTION
R 288	4-01294-462	69.8K	Thin Film, 1%, 50 ppm, MELF Resistor
R 289	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 290	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 291	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 292	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 293	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 294	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 295	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 296	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 297	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 298	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 299	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 300	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 301	4-01302-462	84.5K	Thin Film, 1%, 50 ppm, MELF Resistor
R 303	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 304	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 305	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 324	4-01249-462	23.7K	Thin Film, 1%, 50 ppm, MELF Resistor
R 325	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 326	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 327	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 329	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 331	4-01073-462	348	Thin Film, 1%, 50 ppm, MELF Resistor
R 332	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 333	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 334	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 335	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 336	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 337	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 338	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 339	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 340	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 341	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 342	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 343	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 344	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 345	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 346	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 347	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 348	0-00000-000	UNDECIDED PART	Hardware, Misc.
R 349	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 350	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 351	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 352	4-01464-461	240	Thick Film, 5%, 200 ppm, Chip Resistor
R 353	0-00000-000	UNDECIDED PART	Hardware, Misc.
R 354	4-01493-461	3.9K	Thick Film, 5%, 200 ppm, Chip Resistor
R 355	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 356	4-01493-461	3.9K	Thick Film, 5%, 200 ppm, Chip Resistor
R 357	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 358	0-00000-000	UNDECIDED PART	Hardware, Misc.

REF.	SRS PART	VALUE	DESCRIPTION
R 359	0-00000-000	UNDECIDED PART	Hardware, Misc.
R 360	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 400	4-01347-462	249K	Thin Film, 1%, 50 ppm, MELF Resistor
R 401	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 402	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 403	4-01463-461	220	Thick Film, 5%, 200 ppm, Chip Resistor
R 404	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 405	4-01201-462	7.50K	Thin Film, 1%, 50 ppm, MELF Resistor
R 406	4-01561-461	2.7M	Thick Film, 5%, 200 ppm, Chip Resistor
R 407	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 408	4-01259-462	30.1K	Thin Film, 1%, 50 ppm, MELF Resistor
R 409	4-01355-462	301K	Thin Film, 1%, 50 ppm, MELF Resistor
R 410	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 411	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 412	4-01088-462	499	Thin Film, 1%, 50 ppm, MELF Resistor
R 413	4-01088-462	499	Thin Film, 1%, 50 ppm, MELF Resistor
R 414	4-01088-462	499	Thin Film, 1%, 50 ppm, MELF Resistor
R 415	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 416	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 417	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 418	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 419	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor
R 420	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor
R 421	4-01465-461	270	Thick Film, 5%, 200 ppm, Chip Resistor
R 422	4-01355-462	301K	Thin Film, 1%, 50 ppm, MELF Resistor
R 423	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 424	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 425	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 426	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 427	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 428	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 429	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 430	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 431	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 432	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 433	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 434	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 435	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 436	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 437	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 438	4-01355-462	301K	Thin Film, 1%, 50 ppm, MELF Resistor
R 439	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 440	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 441	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 442	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 443	4-01439-461	22	Thick Film, 5%, 200 ppm, Chip Resistor
R 444	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 445	4-01511-461	22K	Thick Film, 5%, 200 ppm, Chip Resistor
R 446	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 447	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor

REF.	SRS PART	VALUE	DESCRIPTION
R 448	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 449	4-01551-461	1.0M	Thick Film, 5%, 200 ppm, Chip Resistor
R 450	4-01439-461	22	Thick Film, 5%, 200 ppm, Chip Resistor
R 500	4-01059-462	249	Thin Film, 1%, 50 ppm, MELF Resistor
R 501	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 502	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 503	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 504	4-00925-462	10	Thin Film, 1%, 50 ppm, MELF Resistor
R 505	4-00925-462	10	Thin Film, 1%, 50 ppm, MELF Resistor
R 506	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 507	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 508	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 509	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 510	4-01347-462	249K	Thin Film, 1%, 50 ppm, MELF Resistor
R 511	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 512	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 513	4-01059-462	249	Thin Film, 1%, 50 ppm, MELF Resistor
R 514	4-01167-462	3.32K	Thin Film, 1%, 50 ppm, MELF Resistor
R 515	4-01487-461	2.2K	Thick Film, 5%, 200 ppm, Chip Resistor
R 516	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 517	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 518	4-01242-462	20.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 519	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 520	4-01088-462	499	Thin Film, 1%, 50 ppm, MELF Resistor
R 521	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 522	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 523	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 524	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor
R 525	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 526	4-01242-462	20.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 527	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 528	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 529	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 530	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 531	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 532	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 533	4-01493-461	3.9K	Thick Film, 5%, 200 ppm, Chip Resistor
R 534	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 536	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 537	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 538	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 539	4-01489-461	2.7K	Thick Film, 5%, 200 ppm, Chip Resistor
R 540	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 541	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 542	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 543	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 544	4-01218-462	11.3K	Thin Film, 1%, 50 ppm, MELF Resistor
R 545	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 546	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 547	4-01447-461	47	Thick Film, 5%, 200 ppm, Chip Resistor

REF.	SRS PART	VALUE	DESCRIPTION
R 548	4-01469-461	390	Thick Film, 5%, 200 ppm, Chip Resistor
R 550	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 551	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 552	4-00925-462	10	Thin Film, 1%, 50 ppm, MELF Resistor
R 553	4-00925-462	10	Thin Film, 1%, 50 ppm, MELF Resistor
R 600	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 601	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 602	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 603	4-00899-431	P1H104-T-NTC	Thermistor, various
R 604	4-00899-431	P1H104-T-NTC	Thermistor, various
R 605	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 800	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 801	4-01407-461	1	Thick Film, 5%, 200 ppm, Chip Resistor
R 803	4-00899-431	P1H104-T-NTC	Thermistor, various
R 804	4-00899-431	P1H104-T-NTC	Thermistor, various
R 900	4-01597-405	10K	Resistor, Carbon Film, 1/8W, 5%
RX249	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
T 100	6-00195-610	10.7 MHZ	Transformer
U 100	3-00542-360	AD587JR	Integrated Circuit (Surface Mount Pkg)
U 101	3-00819-360	LM7171AIM	Integrated Circuit (Surface Mount Pkg)
U 102	3-00773-360	LM358	Integrated Circuit (Surface Mount Pkg)
U 150	3-00346-329	7812	Voltage Reg., TO-220 (TAB) Package
U 200	3-00774-360	LMC662C	Integrated Circuit (Surface Mount Pkg)
U 201	3-00774-360	LMC662C	Integrated Circuit (Surface Mount Pkg)
U 202	3-00774-360	LMC662C	Integrated Circuit (Surface Mount Pkg)
U 205	3-00653-360	AD8561AR	Integrated Circuit (Surface Mount Pkg)
U 206	3-00659-360	OP284FS	Integrated Circuit (Surface Mount Pkg)
U 207	3-00774-360	LMC662C	Integrated Circuit (Surface Mount Pkg)
U 208	3-00661-360	74HC4051	Integrated Circuit (Surface Mount Pkg)
U 209	3-00661-360	74HC4051	Integrated Circuit (Surface Mount Pkg)
U 210	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 300	3-00563-360	MAX705CSA	Integrated Circuit (Surface Mount Pkg)
U 301	3-00662-360	74HC14	Integrated Circuit (Surface Mount Pkg)
U 303	3-00663-360	74HC08	Integrated Circuit (Surface Mount Pkg)
U 304	3-00662-360	74HC14	Integrated Circuit (Surface Mount Pkg)
U 306	3-00643-360	DG211BDY	Integrated Circuit (Surface Mount Pkg)
U 307	3-00773-360	LM358	Integrated Circuit (Surface Mount Pkg)
U 308	3-00659-360	OP284FS	Integrated Circuit (Surface Mount Pkg)
U 309	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 310	3-00652-360	LTC1452CS8	Integrated Circuit (Surface Mount Pkg)
U 311	3-00652-360	LTC1452CS8	Integrated Circuit (Surface Mount Pkg)
U 312	3-00652-360	LTC1452CS8	Integrated Circuit (Surface Mount Pkg)
U 313	3-00652-360	LTC1452CS8	Integrated Circuit (Surface Mount Pkg)
U 314	3-00658-360	AD7896AR	Integrated Circuit (Surface Mount Pkg)
U 400	3-00946-360	MC145193F	Integrated Circuit (Surface Mount Pkg)
U 401	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 402	3-00654-360	SA602D	Integrated Circuit (Surface Mount Pkg)
U 403	3-00660-360	OP27GS	Integrated Circuit (Surface Mount Pkg)
U 404	6-00193-625	380 MHZ	Voltage Controlled Crystal Oscillator
U 405	3-00650-360	MC12026AD	Integrated Circuit (Surface Mount Pkg)

REF.	SRS PART	VALUE	DESCRIPTION
U 406	3-00773-360	LM358	Integrated Circuit (Surface Mount Pkg)
U 407	3-00655-360	TLC5628	Integrated Circuit (Surface Mount Pkg)
U 500	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 501	3-00149-329	LM317T	Voltage Reg., TO-220 (TAB) Package
U 502	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 503	3-00149-329	LM317T	Voltage Reg., TO-220 (TAB) Package
U 504	3-00112-329	7805	Voltage Reg., TO-220 (TAB) Package
U 505	3-00775-360	LM45CIM3	Integrated Circuit (Surface Mount Pkg)
U 506	3-00742-360	74HC74	Integrated Circuit (Surface Mount Pkg)
U 507	3-00742-360	74HC74	Integrated Circuit (Surface Mount Pkg)
U 508	3-00742-360	74HC74	Integrated Circuit (Surface Mount Pkg)
U 509	3-00813-360	LM311M	Integrated Circuit (Surface Mount Pkg)
U 510	3-00812-360	74HC153	Integrated Circuit (Surface Mount Pkg)
U 511	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 512	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 514	3-00534-360	AD790JR	Integrated Circuit (Surface Mount Pkg)
U 600	3-00346-329	7812	Voltage Reg., TO-220 (TAB) Package
U 800	3-00561-329	7808	Voltage Reg., TO-220 (TAB) Package
UX205	5-00547-504	2.2P	Capacitor, Chip (SMT0805), 50V, 10%, NPO
Y 100	6-00132-620	10 MHZ SC-CUT	Crystal
Y 400	6-00194-620	22.4825 MHZ	Crystal
Z 0	0-00045-013	4-40 MINI	Nut, Mini
Z 0	0-00096-041	#4 SPLIT	Washer, Split
Z 0	0-00098-042	#6 LOCK	Washer, lock
Z 0	0-00231-043	#4 SHOULDER	Washer, nylon
Z 0	0-00243-003	TO-220	Insulators
Z 0	0-00605-025	4-40X1/4 SOCKET	Screw, Allen Head
Z 0	0-00606-025	4-40X1/4 BUTTON	Screw, Allen Head
Z 0	0-00607-025	4-40X1/2 SOCKET	Screw, Allen Head
Z 0	0-00608-025	6-32X1/4 BUTTON	Screw, Allen Head
Z 0	0-00609-025	6-32X5/8 SOCKET	Screw, Allen Head
Z 0	0-00629-066	FOIL;CU 1/2"	Copper Foil Tape, Self Adhesive
Z 0	0-00630-034	#22 INSULATING	Tubing
Z 0	0-00641-031	4-40X3/16 M/F	Standoff
Z 0	0-00642-031	4-40X3/8 M/F	Standoff
Z 0	0-00643-020	4-40X3/16PF UND	Screw, Flathead Phillips
Z 0	0-00644-020	4-40X1/4PF UNDR	Screw, Flathead Phillips
Z 0	0-00645-055	#34AWG MAGNET	Wire, Other
Z 0	0-00902-034	S/S SEAMLESS	Tubing
Z 0	0-00908-030	PROTO MATERIAL	Spacer
Z 0	0-00915-034	CU TUBING 1/16	Tubing
Z 0	1-00323-130	64 PIN STRIP	Connector, Male
Z 0	1-00324-130	64 HDR PIN R/A	Connector, Male
Z 0	3-00668-312	PHOTODIODE	Photodiode
Z 0	7-00557-717	RB-10	Deep-Drawn or Stamping
Z 0	7-00560-721	RB-1	Machined Part
Z 0	7-00636-720	RB-4	Fabricated Part
Z 0	7-00638-721	RB-6	Machined Part
Z 0	7-00639-721	RB-7	Machined Part
Z 0	7-00641-721	RB-9	Machined Part

REF.	SRS PART	VALUE	DESCRIPTION
Z 0	7-00862-720	RB SPACER	Fabricated Part
Z 0	9-00571-924	SPECIALTY #56	Tape, All types

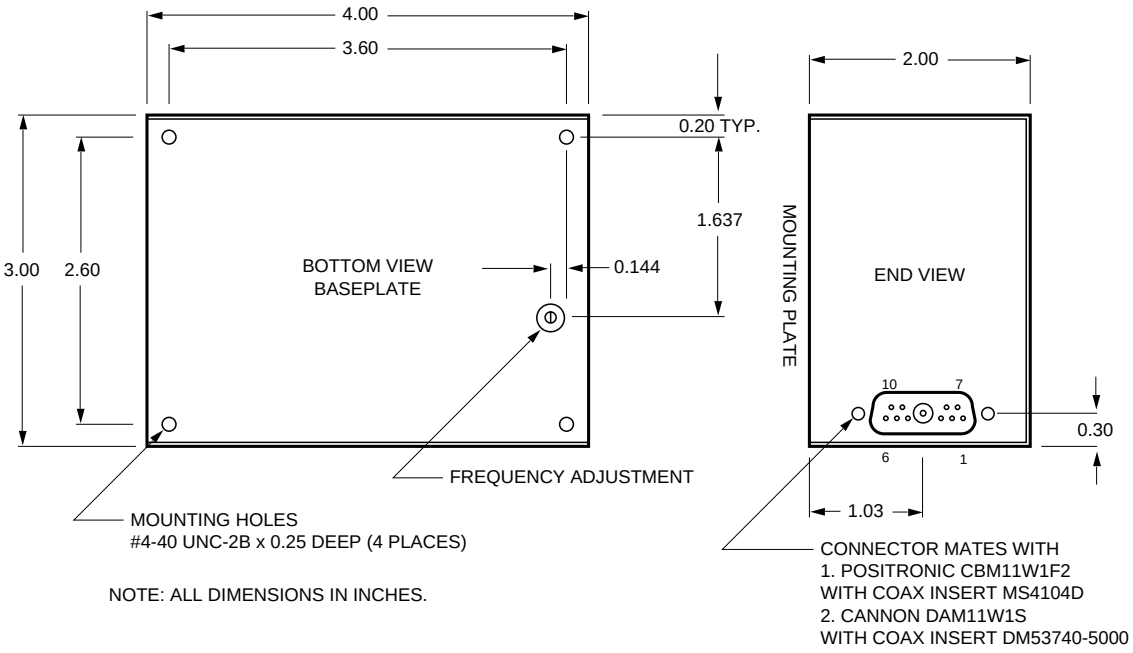

Figure 4. Mechanical Dimensions